Hard Diffraction at HERA

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EIC Collaboration meeting
LBL 12/12/08

Outline

- Hard inclusive diffraction at HERA - success of QCD factorization
- Open questions,puzzles
- (Semi) Exclusive processes
- Gluon fluctuations in nucleons
- Did HERA observed LO BFKL?

Studies of the diffraction at HERA stimulated derivation of new QCD factorization theorems. In difference from derivation in the inclusive case which used closure, main ingredient is color transparency property of QCD

Exclusive processes

$\gamma^* + N \rightarrow \gamma + N(baryonic\,system)$ D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

$\pi + T(A,N) \rightarrow jet_1 + jet_2 + T(A,N)$ Frankfurt, Miller, MS 93 & 03

$\gamma_L^* + N \rightarrow "meson"(mesons) + N(baryonic\,system)$ Brodsky,Frankfurt, Gunion,Mueller, MS 94- vector mesons, small x

Collins, Frankfurt, MS 97 - general case

provide new effective tools for study of the 3D hadron structure, high energy color transparency and opacity and chiral dynamics

Fragmentation processes including diffraction

Proof in QCD - Collins 98

Diffractive phenomena - inclusive diffraction and measurement of diffractive pdf's

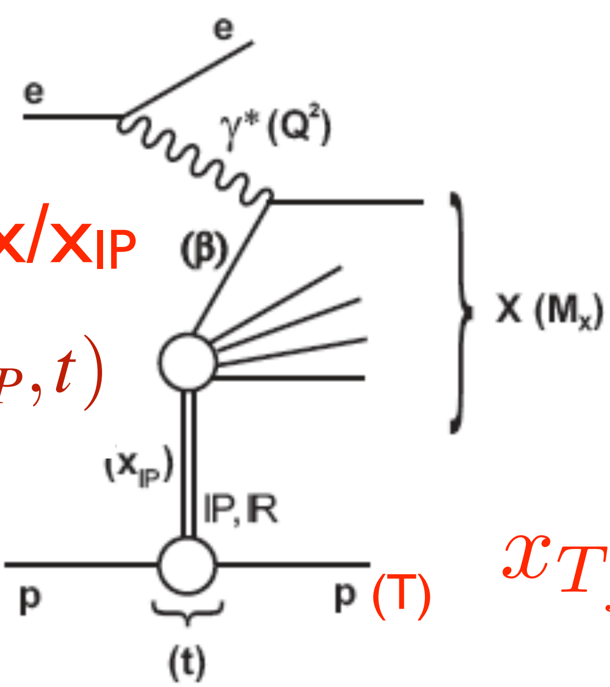
Collins factorization theorem: consider hard processes like

$$\gamma^* + T \to X + T(T'), \quad \gamma^* + T \to \; jet_1 \; + \; jet_2 + X + T(T')$$

one can define conditional (fracture - Trentadue &Veneziano) parton distributions

$\beta \equiv x/x_{IP}$

$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$$

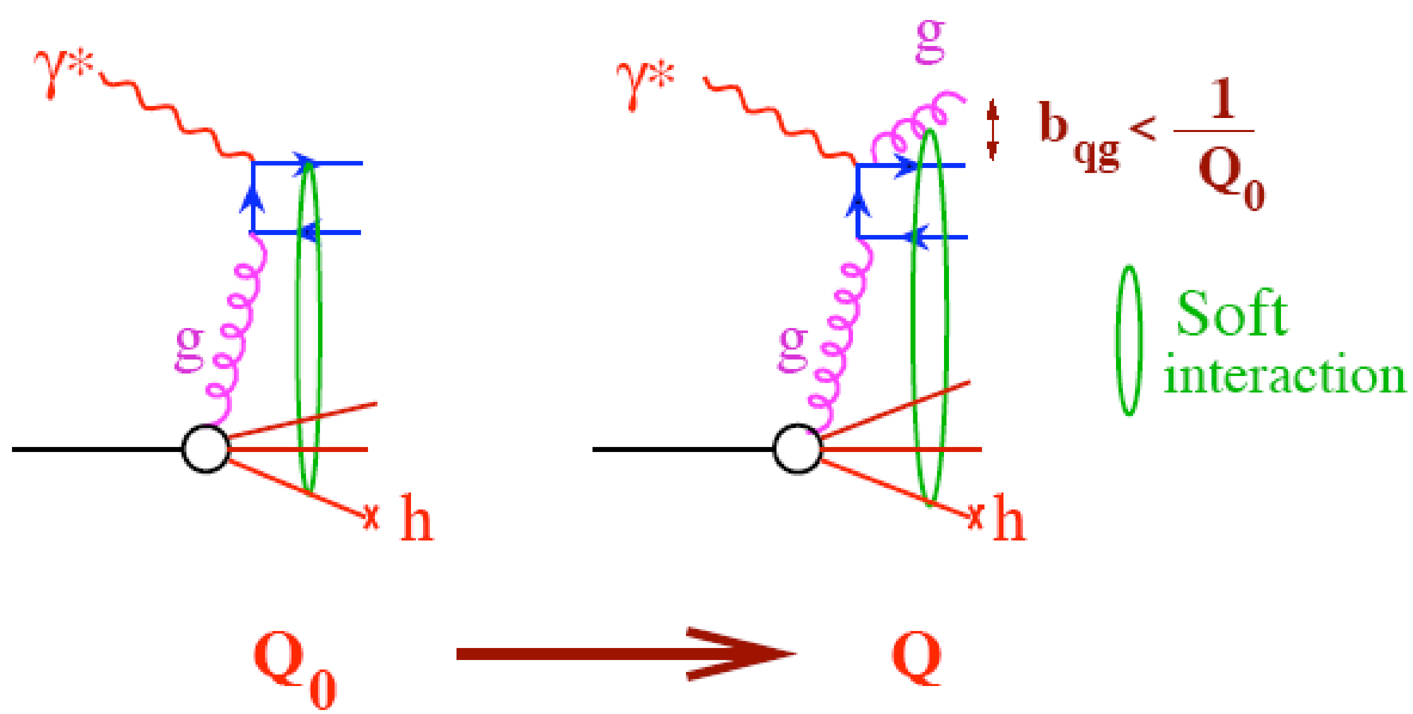


$$x_{T_f} = 1 - x_{I\!P}$$

Theorem: for fixed $x_{I\!P}, \; t$ universal fracture pdf + the evolution is the same as for normal pdf's

Theorem violated in dipole model of diffraction in several ways

Physics of factorization theorem: Soft interactions between "h" and the partons emitted in the $\gamma^* - parton$ interaction does not resolve changes of color distribution between the scale $Q_0 \gg soft\ scale$ and $Q^2 > Q_0$



$\rightarrow$ Production of "h" when a parton at x, Q^2 is hit is the same as when an "ancestor" parton is hit at x, Q_0^2.

Additional assumption to reduce number of free parameters in the fits - *soft Regge factorization*:

$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t)(f_{j/I\!P}(\beta, Q^2) + f_{I\!R/p}(x_{I\!R}, t)(f_{j/I\!R}(\beta, Q^2)$$

☞ *Measurement of $F_2^{D(4)}$*

Very good for j=q, good for j=g for small and medium β from scaling violation

☞ *Measurement of dijet production*

Very good for j=g especially for medium and large β. However only large Q^2

☞ *Diffractive charm production*

Very good for j=g . Feasible for medium and large β and at moderate Q^2 . However statistical accuracy is not as good.

Good consistency between H1 and ZEUS

Diffractive DIS: **Inclusive DIS:**

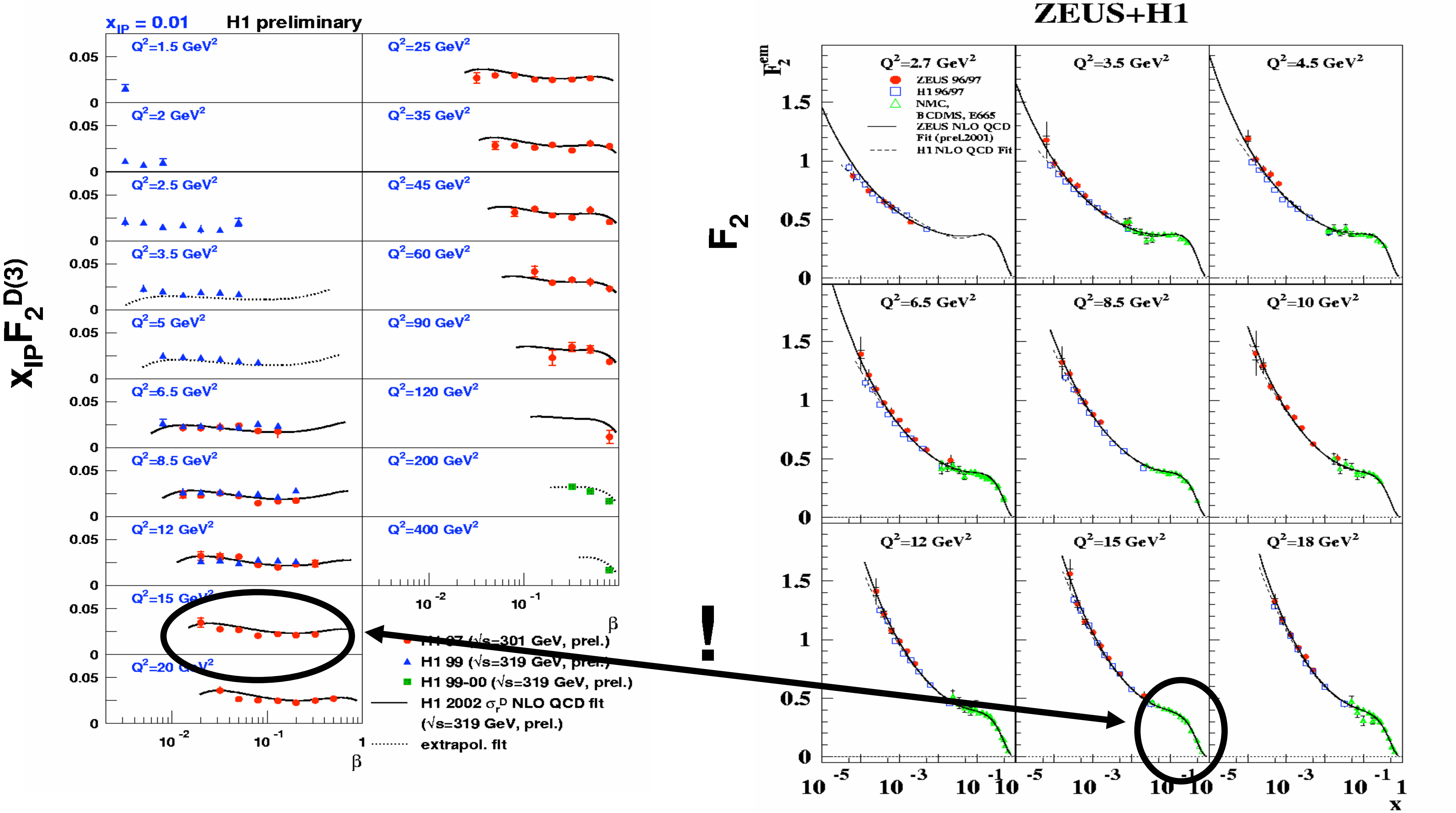


Fig. 8: Left: the diffractive structure function of the proton as a function of β (from [7]). Right: the structure function of the proton as a function of x_B (from [8]). The two highlighted bins show the different shapes of F_2^D and F_2 in corresponding ranges of β and x_B at equal Q^2.

Different scaling violation at large x/β - signal for importance of gluons in diffraction

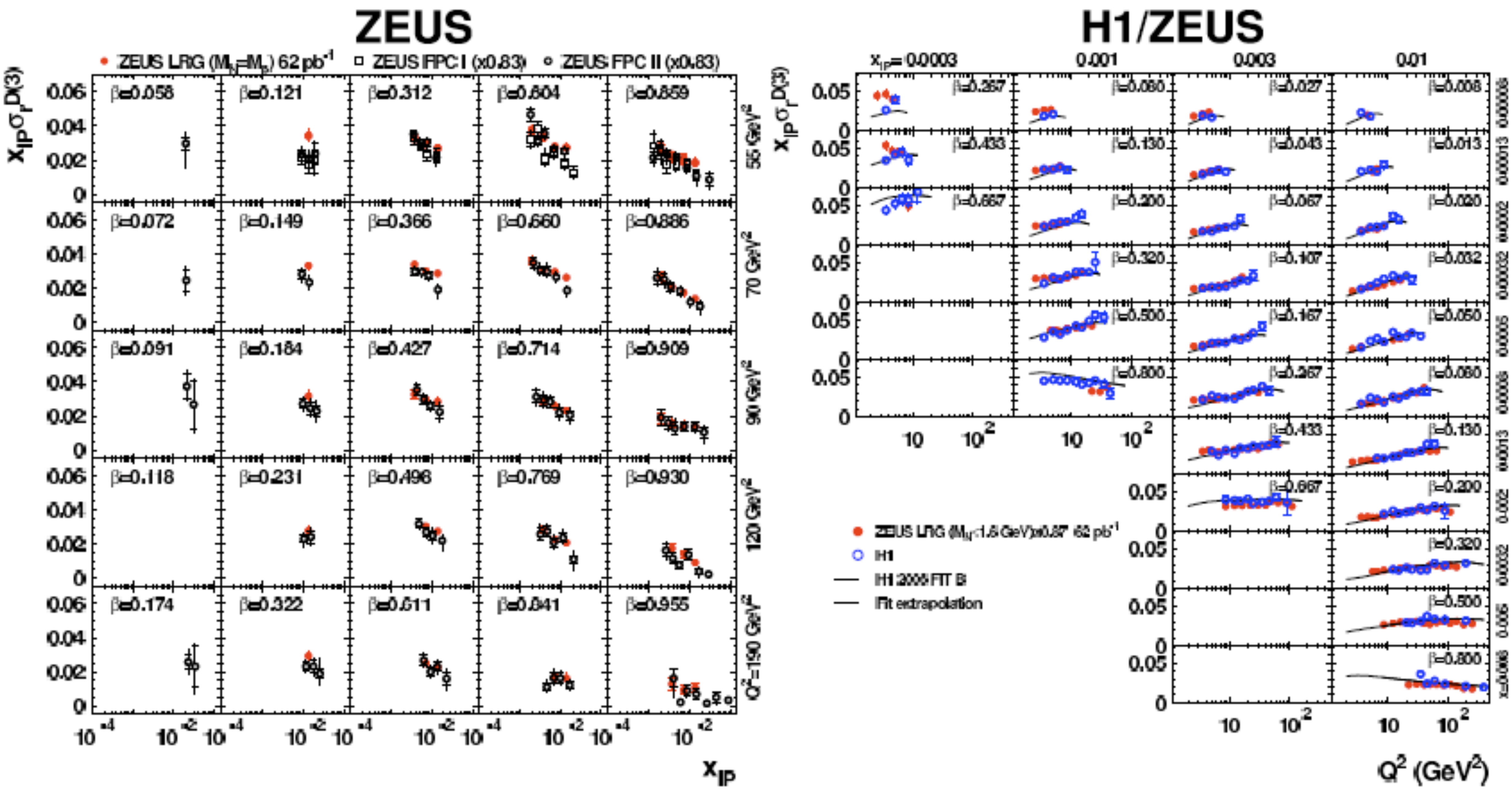
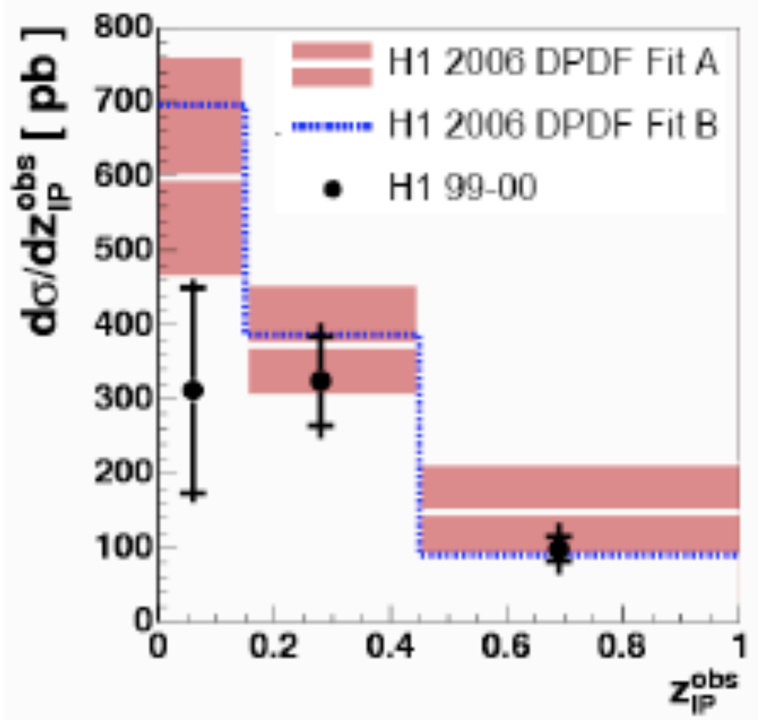
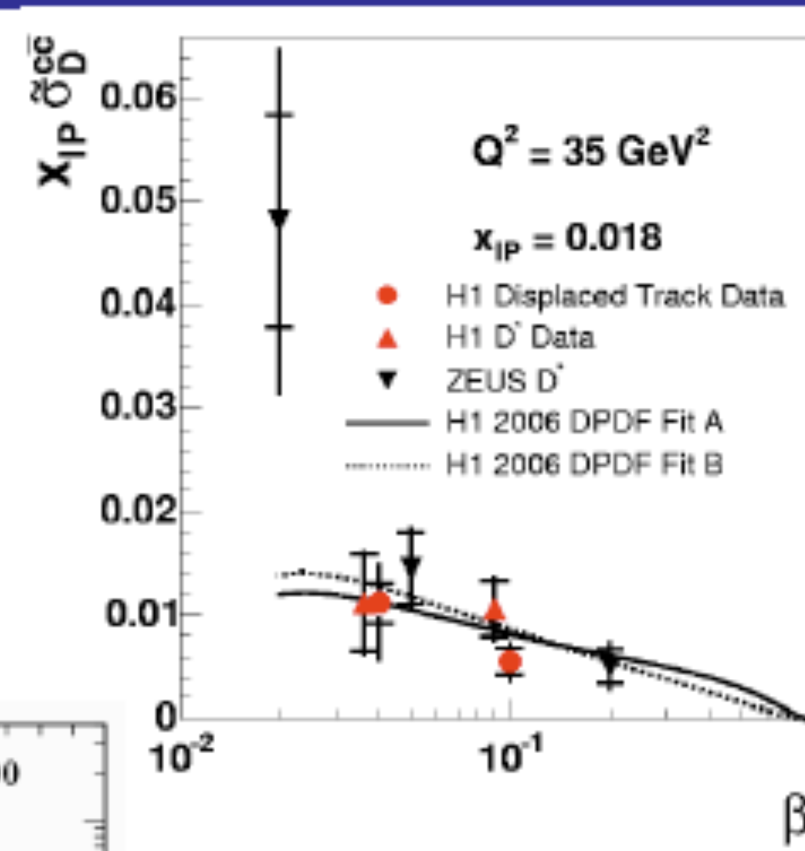


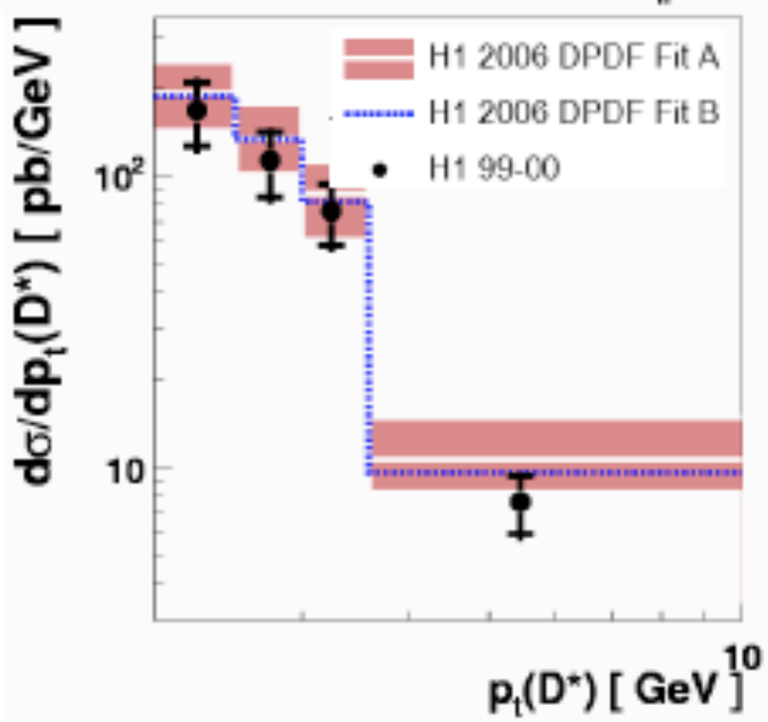
Fig. 2: Comparison of the reduced cross section in inclusive diffractive DIS as a function of (left) $x_{I\!P}$ for fixed β and Q^2 for the LRG and M_X methods and (right) Q^2 for fixed $x_{I\!P}$ and β for H1 and ZEUS data using the LRG method.

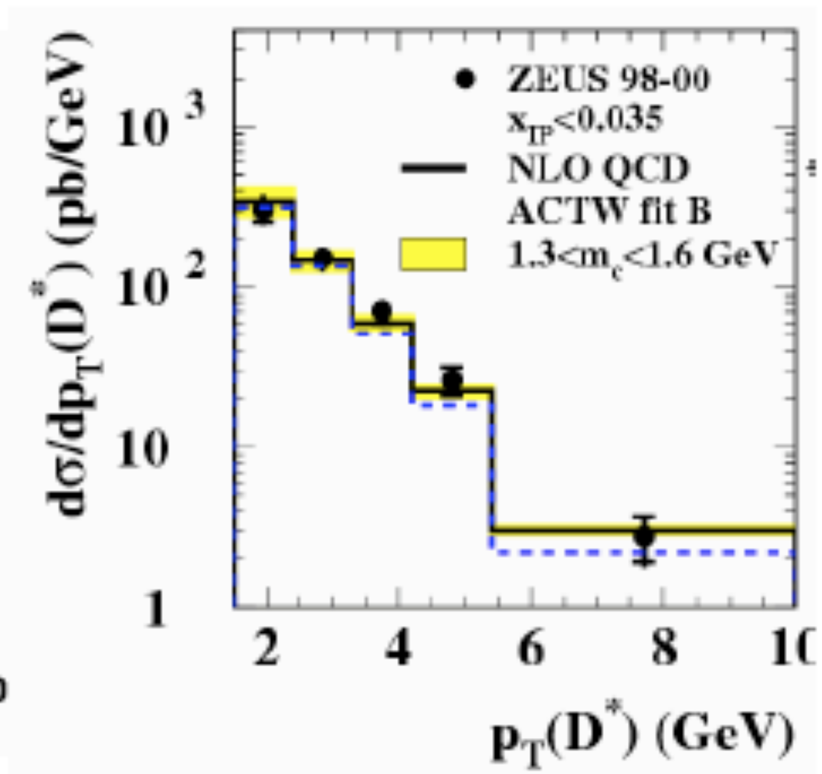
Different methods of measurements by H1 and ZEUS agree with ~10% accuracy

D* production in Diffractive DIS





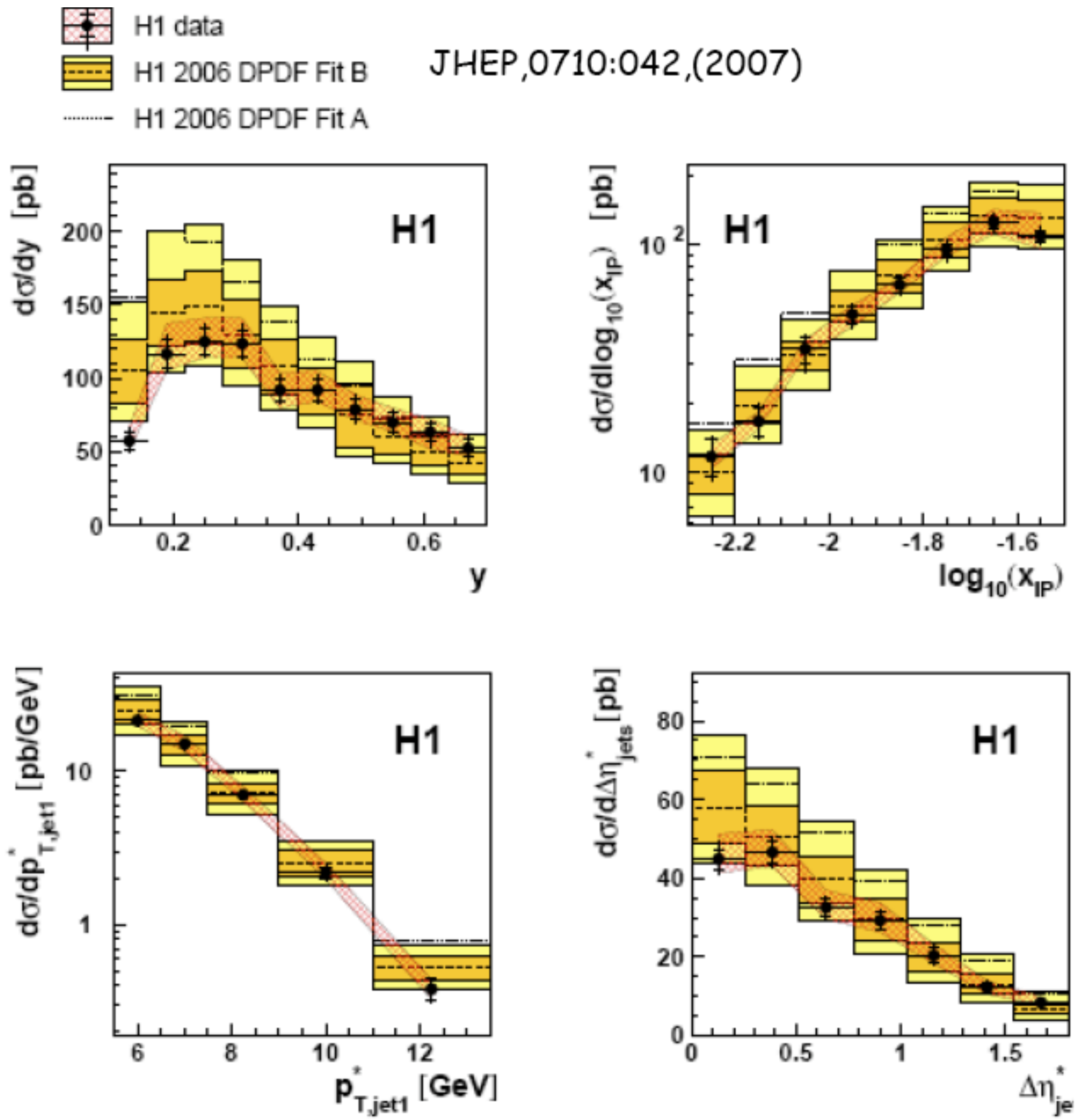




NLO calculations (HVQDIS) provide good description of diffractive charm data
→ support QCD factorization

Dijet production

JHEP,0710:042,(2007)



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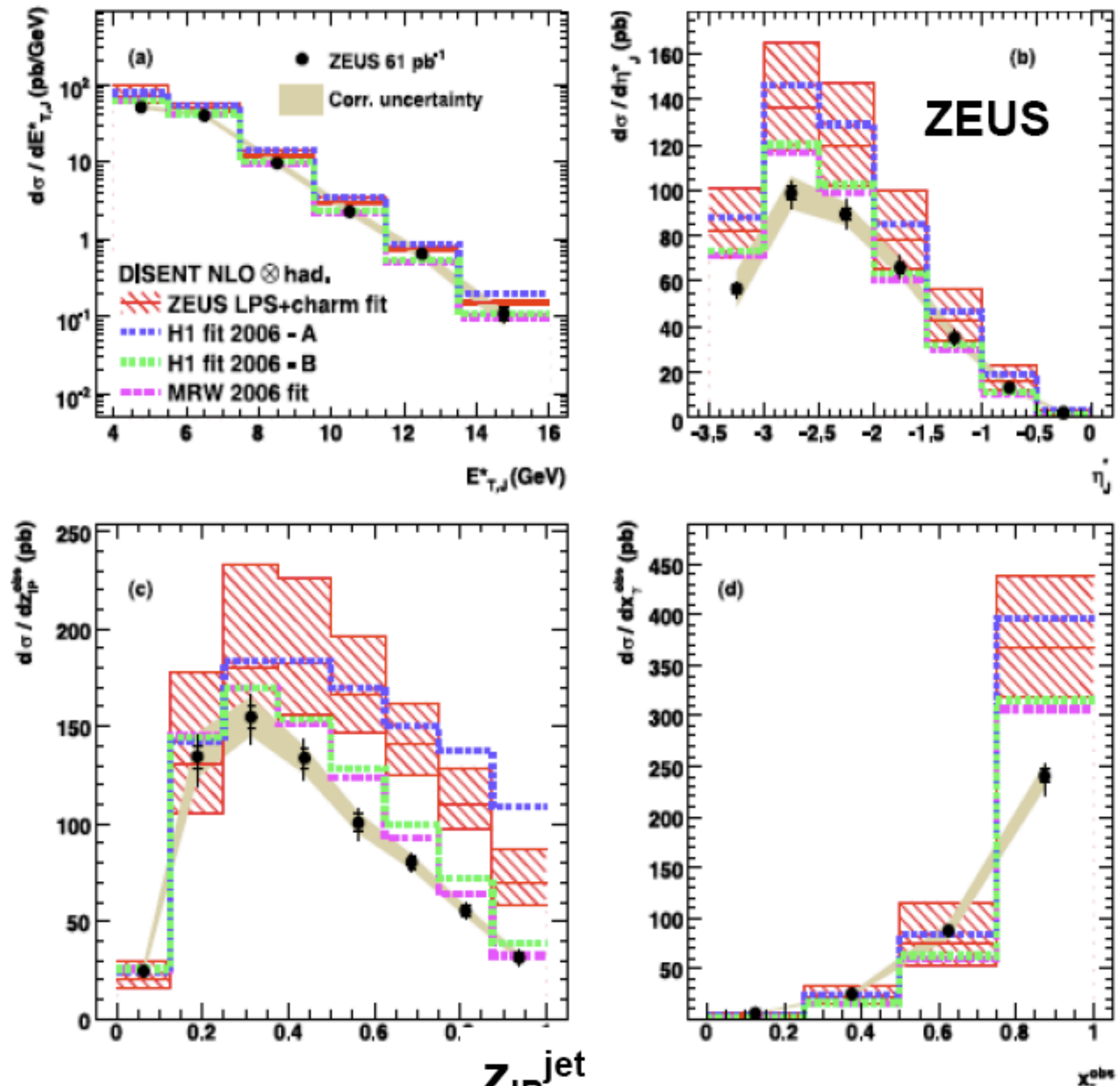
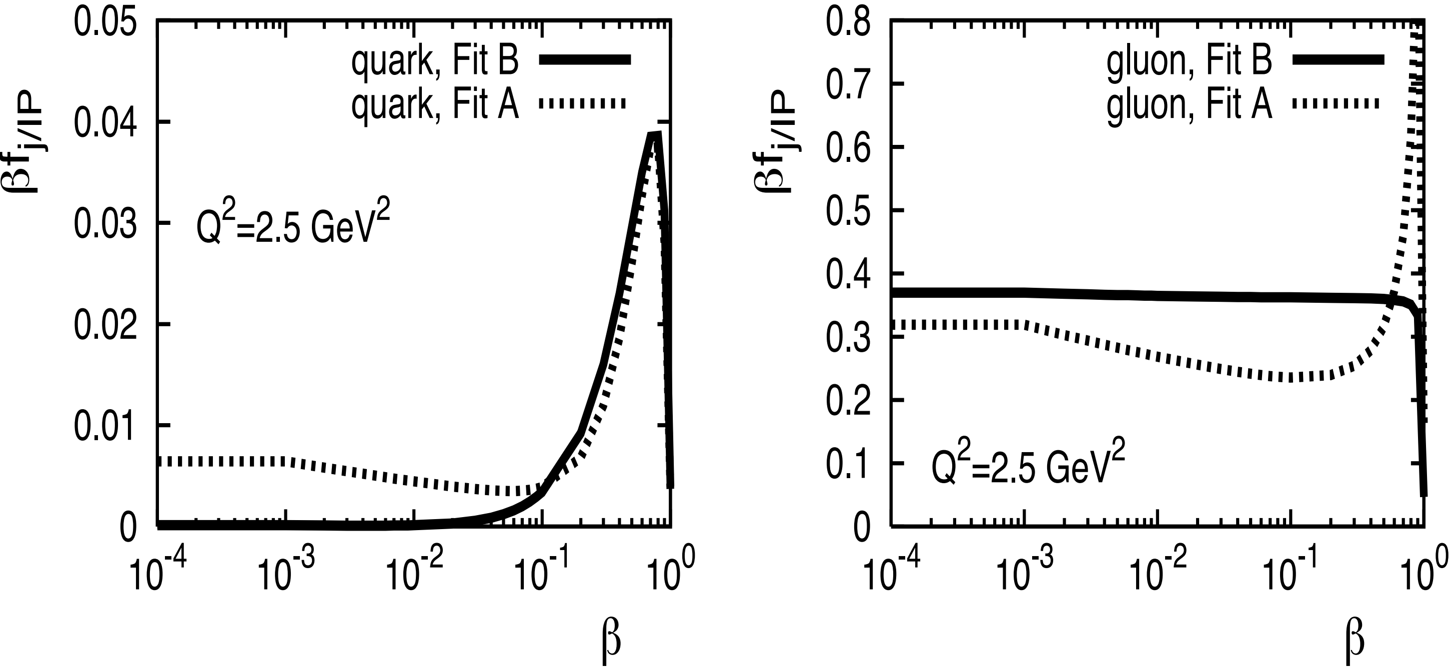


z_{IP}^{jet}

Agrees with QCD factorization. Allows to constrain gluon dPDF especially at large β

$$\boxed{z_{I\!P} \equiv z \equiv \beta}$$



gluon dPDF >> quark dPDF

The quark and gluon diffractive PDFs at Q^2 =2.5 GeV^2 as a function of β

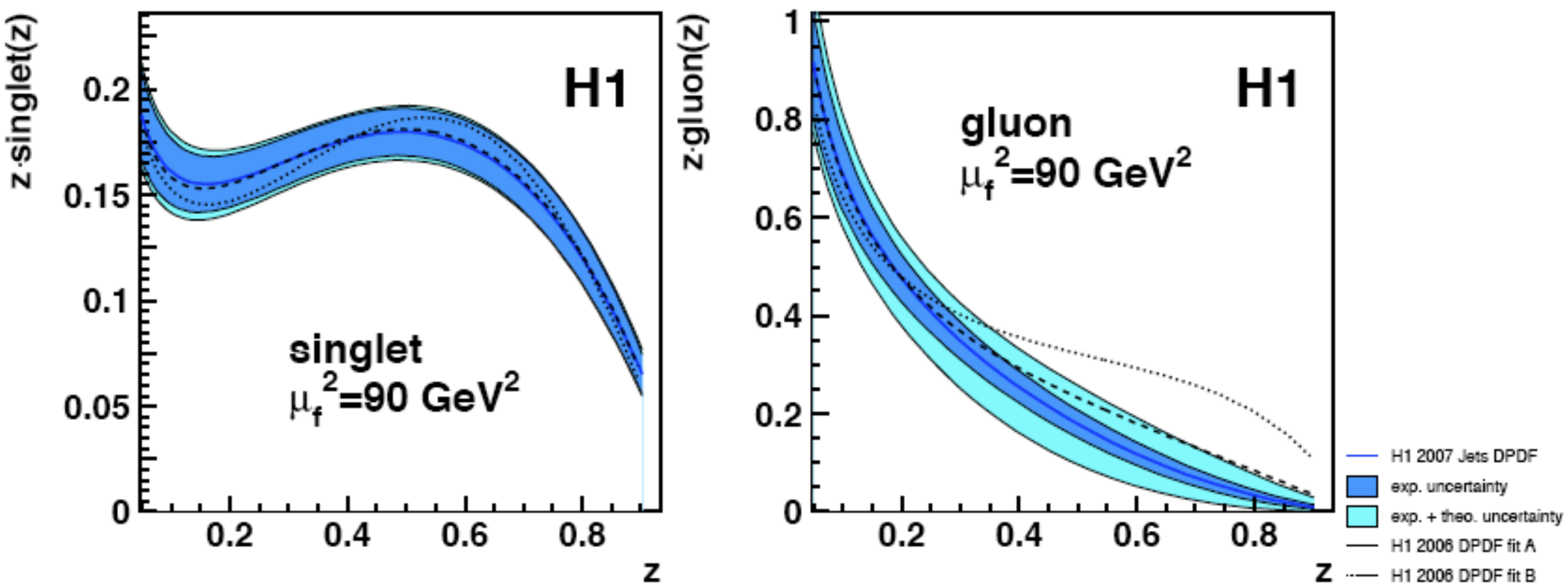
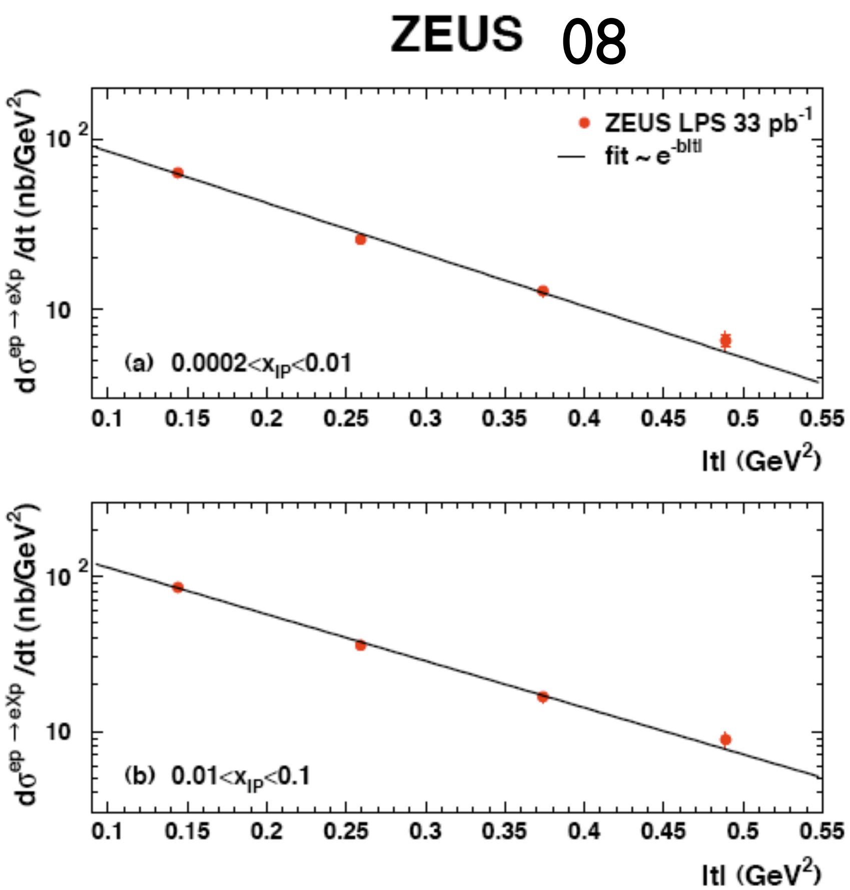
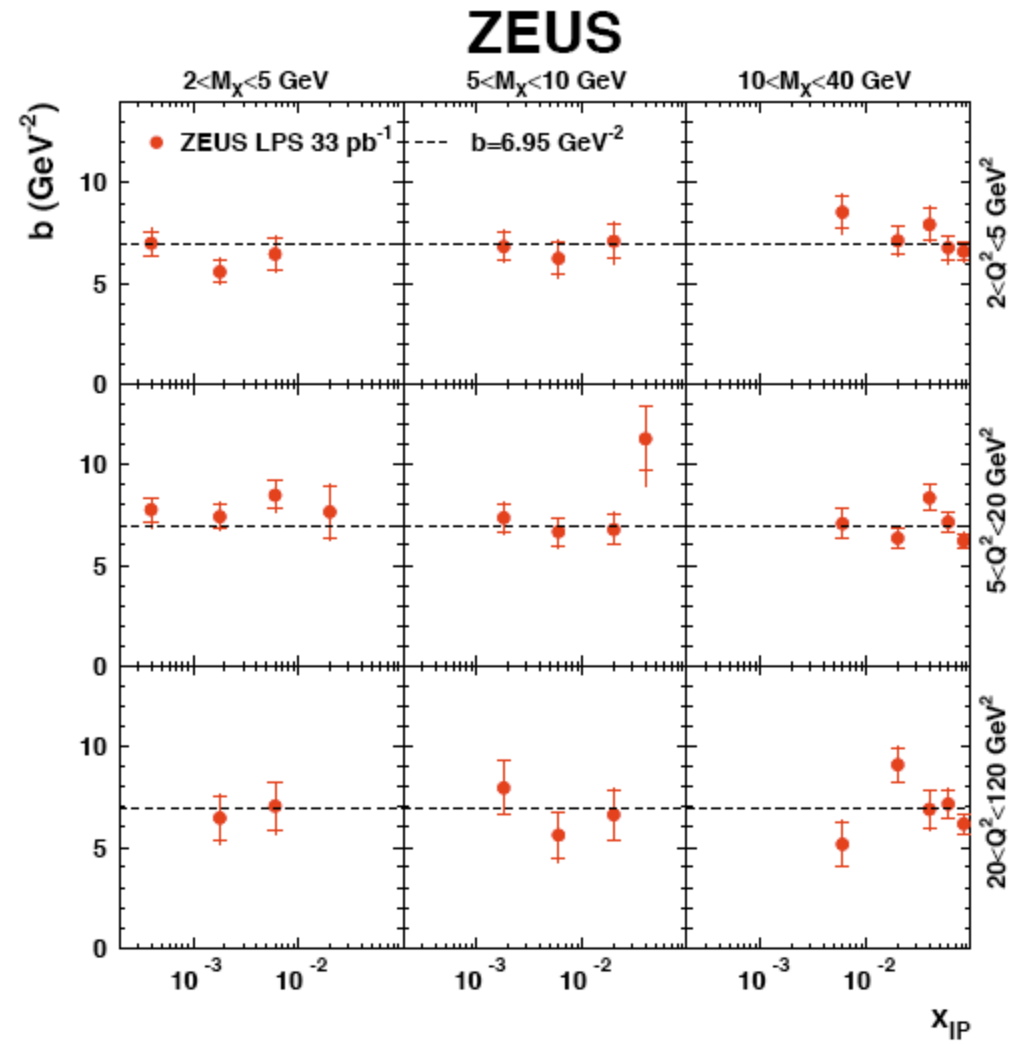


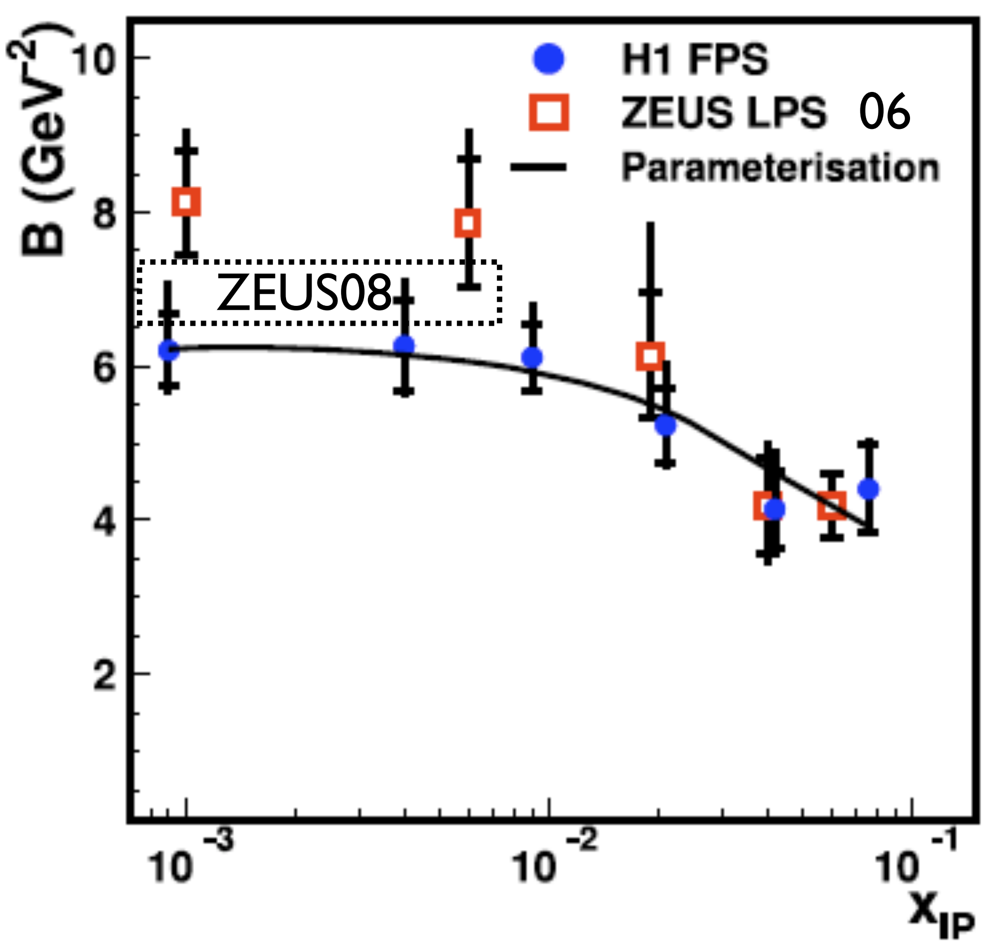
Fig. 4: Comparison of dPDFs for the quark and gluon densities when simultaneously fitting inclusive and jet data (bands) and when fitting inclusive only (lines).

QCD factorization for diffraction allows to determine in a model independent way LT shadowing for nuclear pdfs - LF & MS & Guzey - Guzey's talk later today





ZEUS08 B=7 ±0.3 GeV^{-2}



Very good agreement between current ZEUS and H1 data for t-slope

Diffraction in the quark channel is pretty modest - 10- 15% - far from black regime and $\alpha_{I\!P}$ dependence is very close to that of soft processes - close to expectation of the aligned jet model + QCD evolution - H. Abramowicz, LF & MS 95

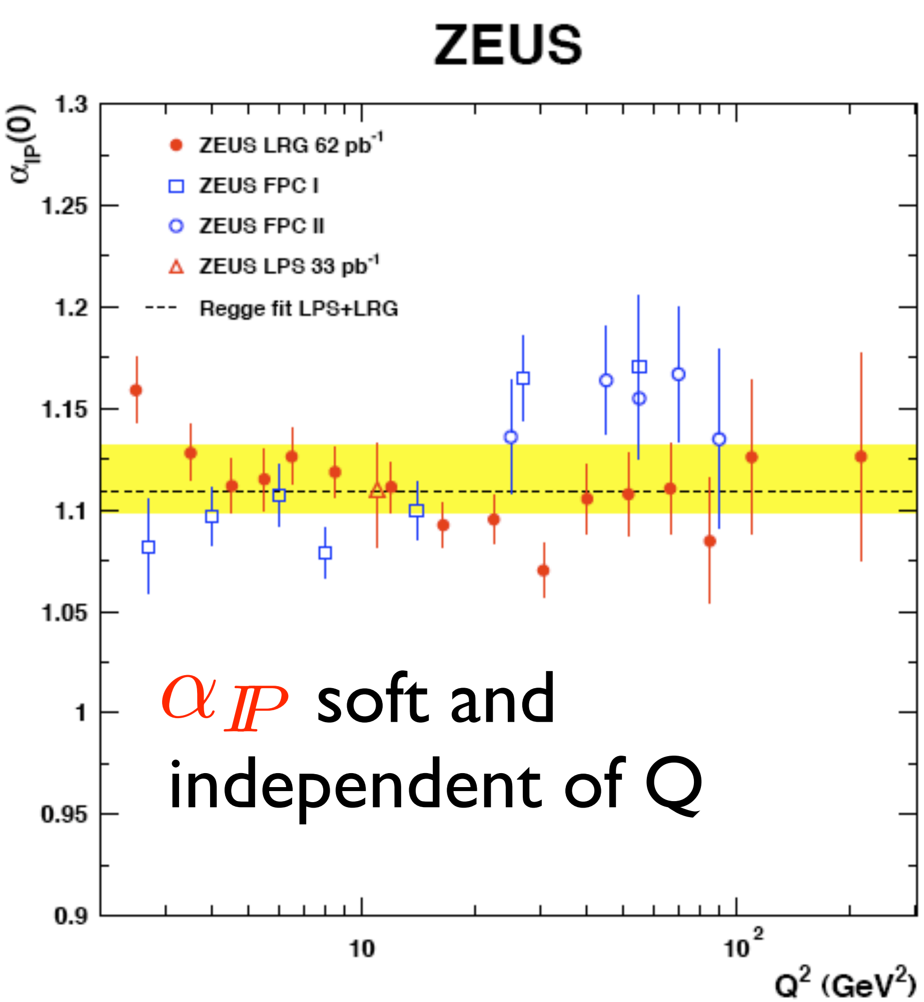
H1

$$\text{Fit A}: \underline{\alpha_{I\!P}(0) = 1.118 \pm 0.008\,,} \quad n_{I\!R} = (1.7 \pm 0.4) \times 10^{-3}\,,$$
$$\text{Fit B}: \underline{\alpha_{I\!P}(0) = 1.111 \pm 0.005\,,} \quad n_{I\!R} = (1.4 \pm 0.4) \times 10^{-3}$$

Current fits to soft hadron - hadron interactions find

$\alpha_{I\!P}(0)$=1.09 - 1.10

☛Diffraction at HERA is due to the interaction of hadron size components of γ* not small dipoles



$$\alpha'_{I\!P}(ZEUS) = -0.01 \pm 0.06(stat) + 0.04 - 0.08(syst) GeV^{-2}$$

$$\alpha'_{I\!P}(H1) = 0.06 + 0.19 - 0.06 GeV^{-2}$$

Traditional soft value $\alpha'_{I\!P}(soft) = 0.25 GeV^{-2}$

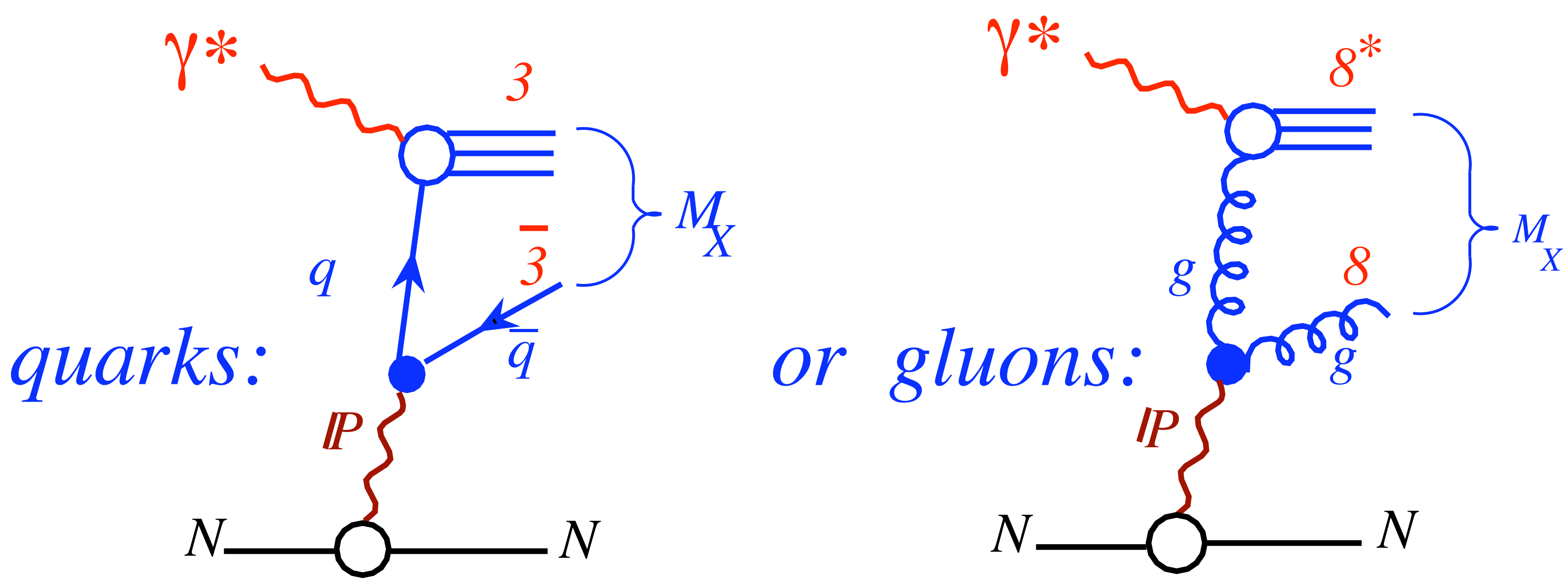
But $\alpha'_{I\!P}(HERA\,exclusive) = 0.12 GeV^{-2}$

Diffraction at HERA is governed by scattering of configurations which interact in a soft way - but evolve via DGLAP evolution to larger Q. Contribution of small dipoles is small.

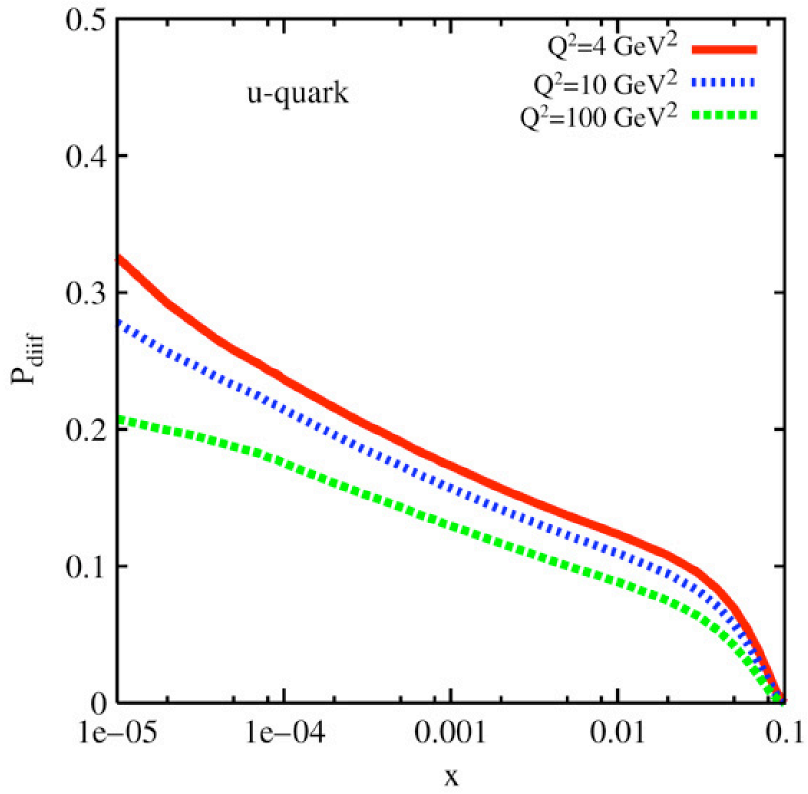
To characterize the strength of interaction we can use factorization theorem to define probability

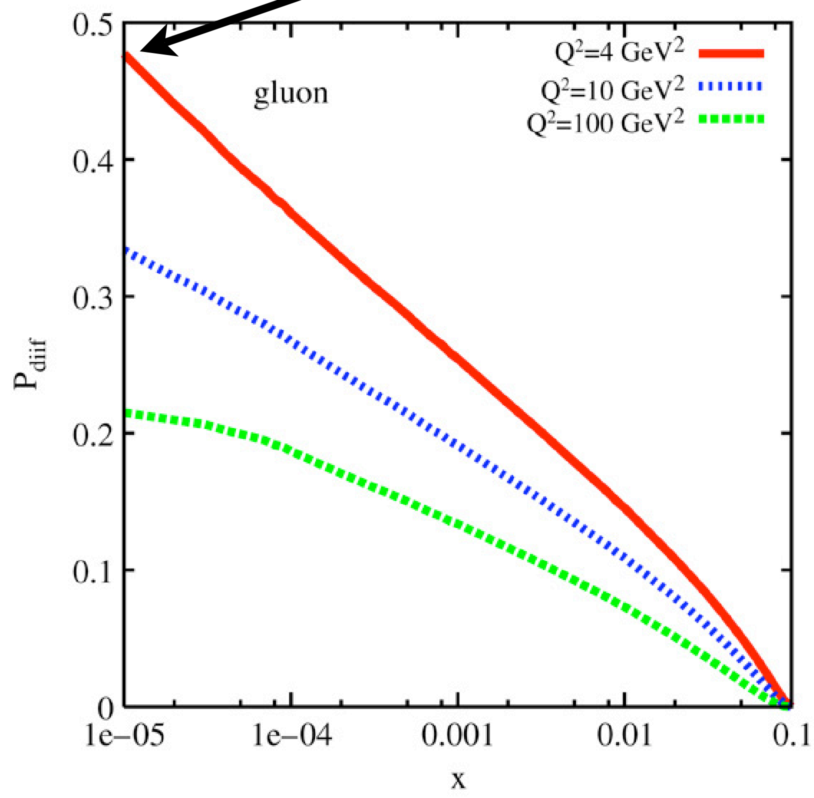
$$P_j(x,Q^2) = \frac{\int f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)\,dt\,dI\!P}{f_j(x,Q^2)}$$

of diffractive gaps induced by scattering off parton j



If the interaction in the gluon sector at small x reaches strengths close to the unitarity limit we should expect that P_g is rather close to 1/2 and much larger than P_q.





Evidence for onset of BDR at HERA for gluons at Q=2 GeV

The probability of hard diffraction on the nucleon, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right) based on the current HERA data. Guzey et al

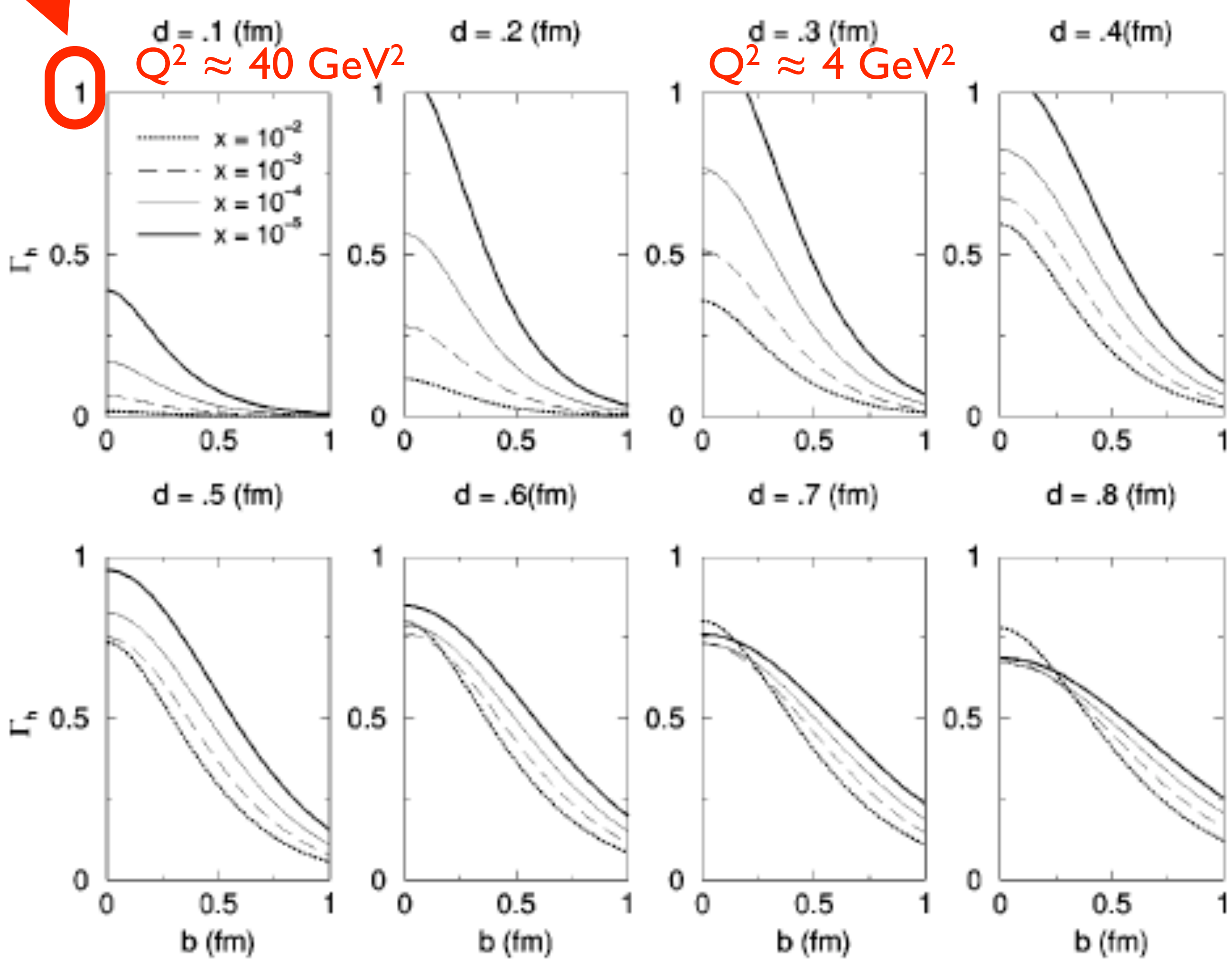
Warning - curves for $x <$ few $\cdot 10^{-4}$ is extrapolation of the fits.

For gluon channel $B=7\ GeV^{-2}$ leads to impact factor $\Gamma_{gg}(b=0, Q^2=4\ GeV^2) \sim 1$ for $x \sim 10^{-3}$ $\Rightarrow$ new regime? increase of B?

Consistent with analysis of the exclusive processes at HERA

$$\Gamma_h(s,b) = \frac{1}{2is(2\pi)^2}\int d^2\vec{q}\exp(i\vec{q}\cdot\vec{b})A_{hN}(s,t)$$

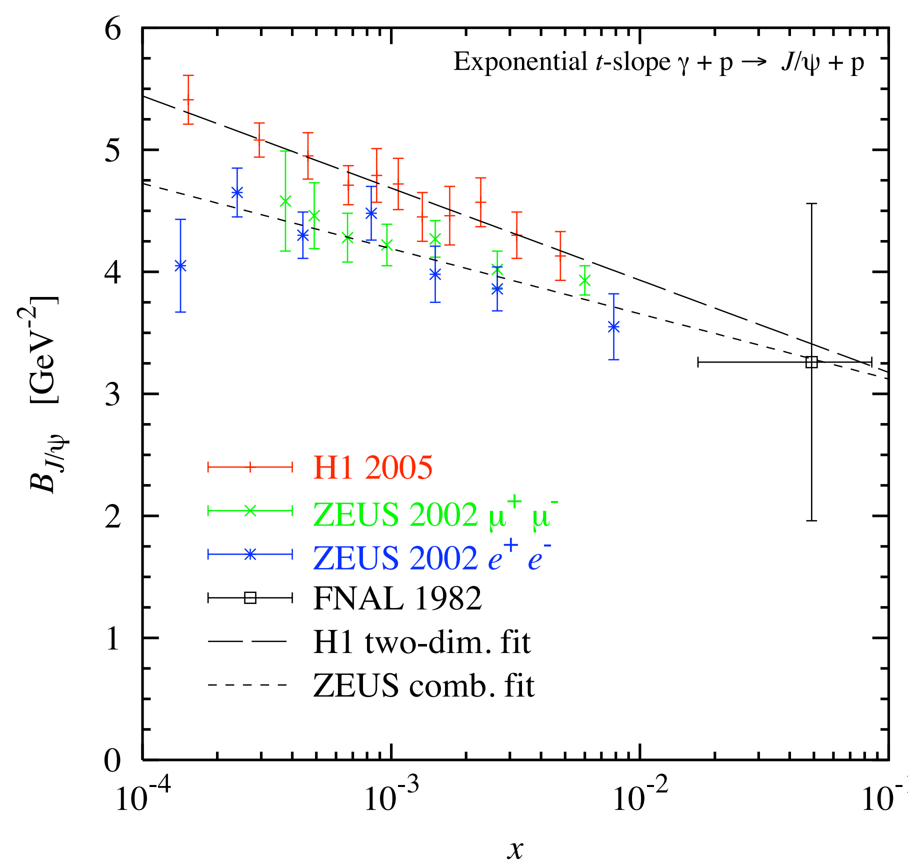
BDR



$$h = q\bar{q};\ \Gamma_{gg} = \frac{9}{4}\Gamma_{q\bar{q}}$$

Rogers et al 04

used information about J/psi photo production at FNAL



Two interesting topics which I can discuss only very briefly.

Hard diffraction induced by real photon $\gamma + p \to jet_1 + jet_2 + X + p$

generic jets or
containing D-mesons

important variable x_γ - fraction of the photon + component carried by 2 jets

$x_\gamma = 1$ - direct photons; $x_\gamma < 0.9$ - resolved photons

Naive expectation - factorization should work for direct photons and cross section should be suppressed for resolved photon.

	direct	resolved	charm
☛ $E_{jet} < 7$ GeV	suppr. ~0.5	suppr. ~0.5	factorization
☛ $E_{jet} > 10$ GeV	factorization	suppr. ~0.5	

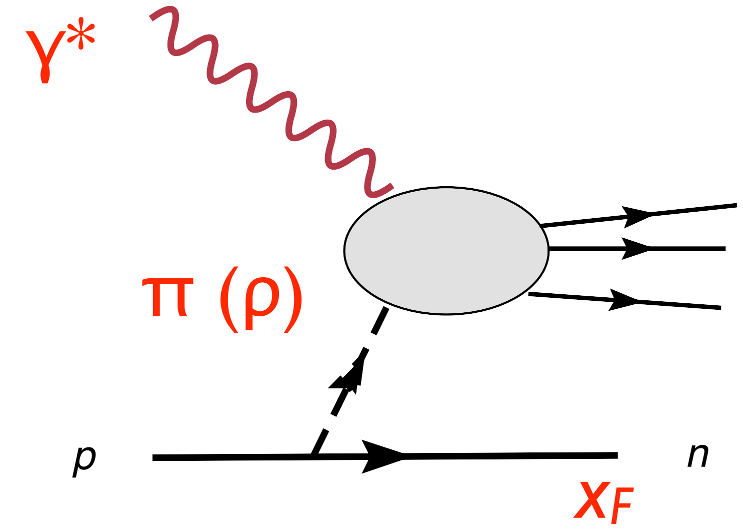
puzzle, especially since for
$Q^2 >$ few GeV^2 no suppression } Need a better theory?

Production of neutrons in DIS in the nucleon fragmentation region

Collins factorization theorem is applicable and appears to hold.

Two scenarios of neutron production suggested for small x:

- *Pion (heavier meson) exchange* - starting from Sullivan 71 Measure pion pdfs ?! With realistic πNN form factors ρ is a must to fit the data



- *Fragmentation after removal of small x parton, Koepf et al 97. Matching to soft dynamics - lack of long range correlations - neutron multiplicity for the limit $x/(1-x_F) << 1$ is the same for quark and gluon removal and similar to soft processes*

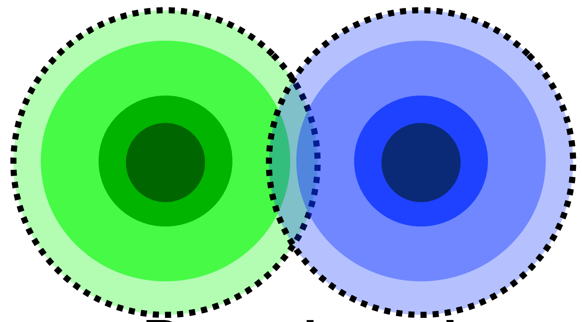
HERA data

☝ Neutron spectra in soft and hard processes are very similar (up to small shadowing effects for soft case)

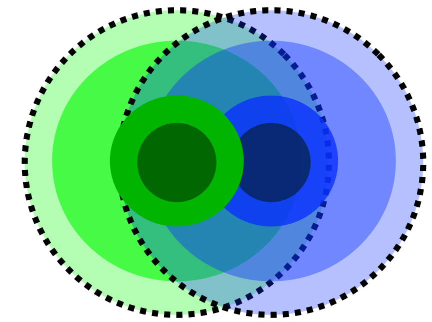
☝ Similar for quark and gluon removal - very difficult for meson models, predicted by fragmentation approach - another evidence for smooth soft - hard connection.

Few comments on “ classical” hard exclusive processes at HERA -
complementing M.Diehl & A.Sandacz talks

Small x GPDs -
link to LHC

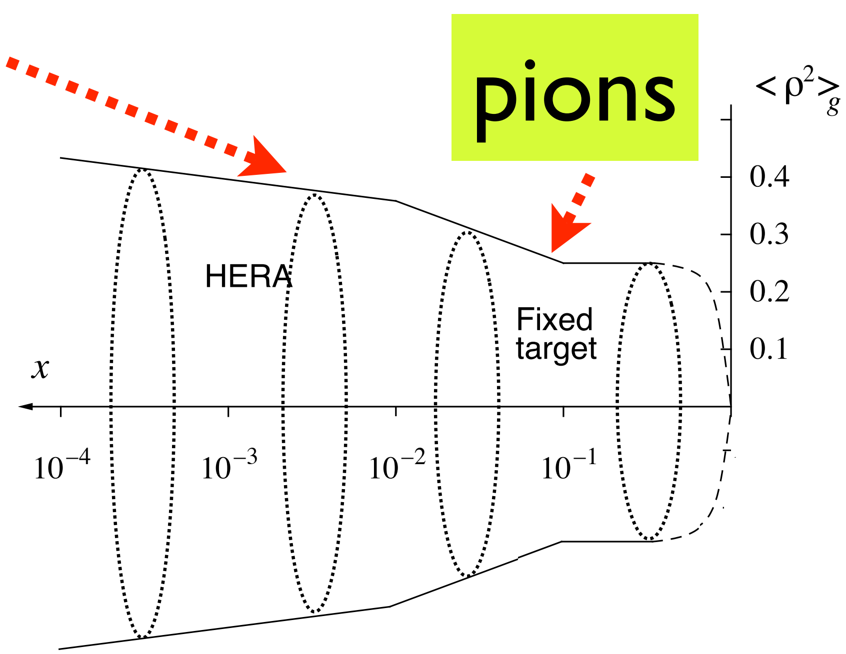


Peripheral
pp collisions



Central
pp collisions

$\langle \rho^2 \rangle_{e.m.}$



$$\langle \rho^2 \rangle_g = \frac{\partial}{\partial t} \frac{G(x.t)}{G(x,0)}$$

Interplay of hard and soft interactions in pp collisions, rate of multiple hard collisions is determined by the value of $<\rho^2_g>$ as compared to much larger radius of soft interactions. Note PYTHIA assumes $<\rho^2_g>=<\rho^2_q>$ x independent and a factor ~ 2 smaller than given by analysis of GPDs from J/ψ production

DVCS - another evidence for soft boundary condition

Analysis of L.Schoeffel, 07 of R - ratio of DVCS and diagonal amplitudes at t=0 (uncertainties in PDFs are canceled)

$$R = \frac{A_{DVCS}(W, Q^2, t=0)}{A_{\gamma^* p \to \gamma^* p}(W, Q^2)}$$

Predictions:

Soft boundary condition

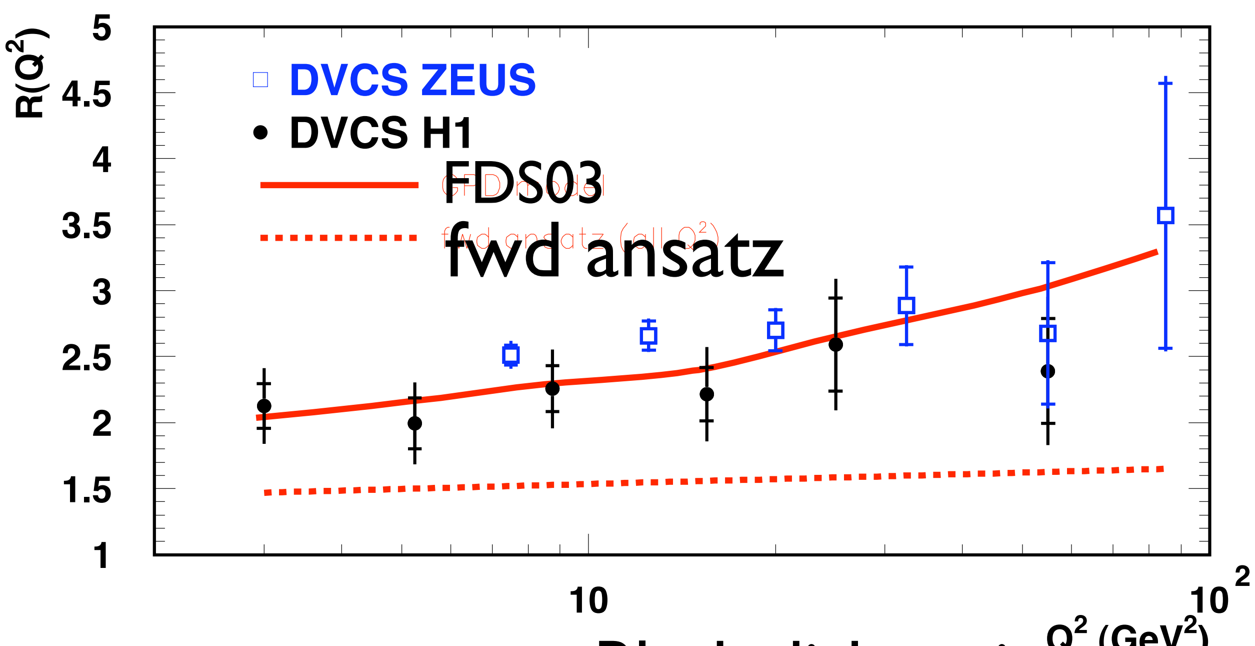
R=2 and slowly increasing with Q

Freund, Frankfurt, MS 97

Black disk regime

R=1 for $Q^2 < Q_s^2$

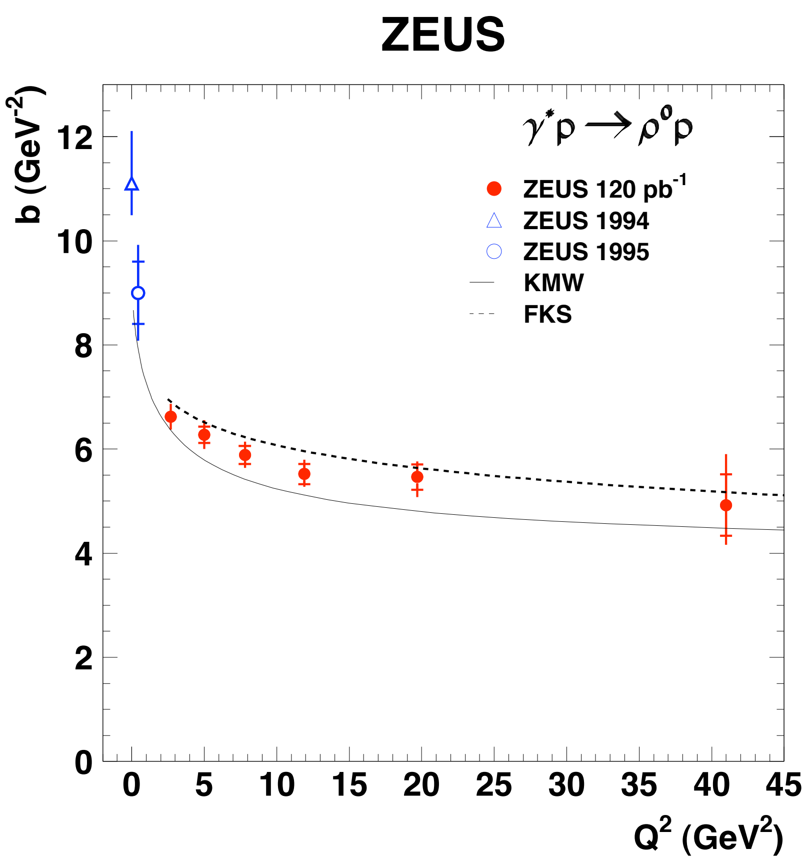
Guzey et al 01



Black disk regime

FDS= Freund et al - NLO
with soft boundary condition

Implications for color transparency studies with nuclei



Drop of the t -slope B ($\frac{d\sigma}{dt} = A\exp(Bt)$) is well reproduced by dipole models (in case of FKS actually a predicti ago)

$$\frac{B(Q^2) - B_{2g}}{B(Q^2=0) - B_{2g}} \sim \frac{R^2(dipole)}{R^2_\rho}$$

$$\frac{R^2(dipole)(Q^2 \geq 3GeV^2)}{R^2_\rho} \leq 1/2$$

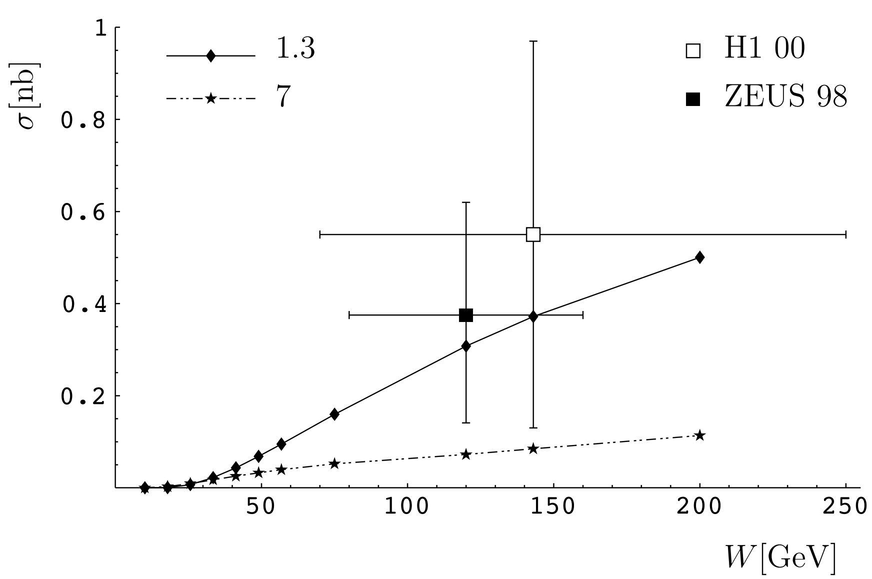
Convergence of B for ρ-meson electroproduction to the slope of J/psi photo(electro)production - **direct proof of squeezing.**

Expect significant CT effects for meson production for $Q^2 \geq 3GeV^2$

sensitivity already at Jlab 6 &12

Theoretical argument - what is better accurate account of geometry of dipole interactions in VM production or NLO calculation? ϒ - smallest dipole available.

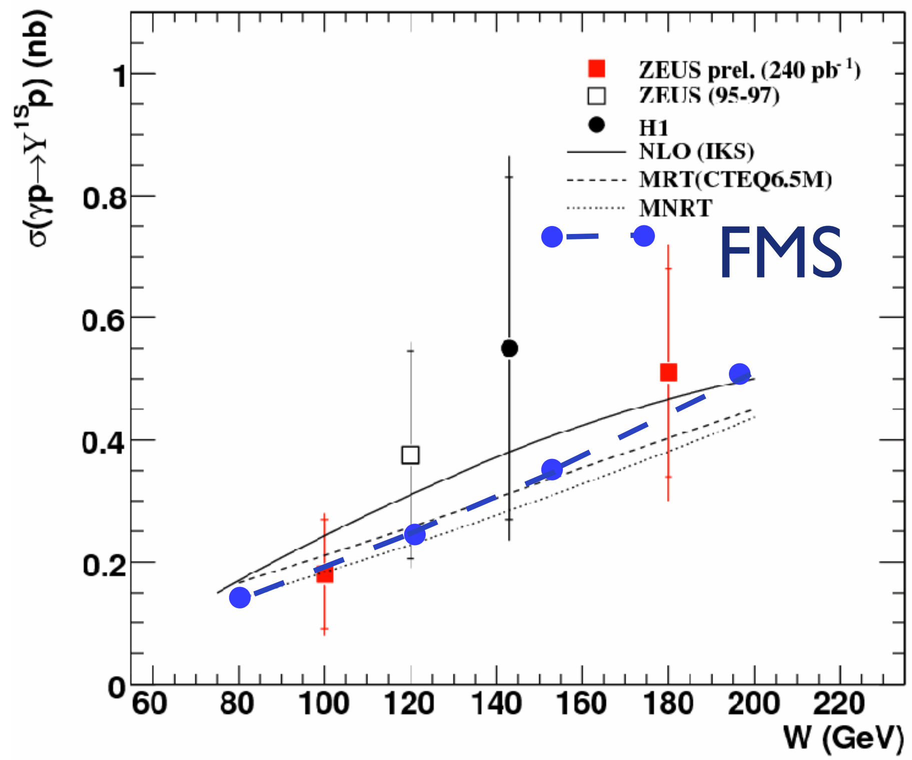
$\mu_F = \mu_R$



Ivanov et al (IKS)

Strong dependence of NLO result on μ_R. Data described for very small μ_R

open questions - energy conservation and related issues with gauge invariance. treatment of the meson wave function



New ZEUS 240 pb^{-1} two data points

NLO calculations done by Ivanov, Krasnikov, Szymanowski (IKS)[hep-ph/0412235]

MRT – Martin, Ryskin, Teubner, based on CTEQ6.5M gluon.

MNRT – Martin, Nockles, Ryskin, Teubner, based on diffractive J/Ψ data alone.

FMS - Frankfurt, McDermott, Strikman 98

Novel way to use hard VM production: measuring gluon fluctuations in nucleons

MS + LF + C.Weiss, D.Treleani PRL 08

Reminder - soft inelastic diffraction at =0

$|h\rangle = a_1 |1\rangle + a_2 |2\rangle$

h

absorber with
same absorption
for "1" and "2"

h

$|final\rangle = \lambda(a_1 |1\rangle + a_2 |2\rangle) = \lambda |h\rangle$

only elastic scattering

$|h\rangle = a_1 |1\rangle + a_2 |2\rangle$

h

absorber with
different absorption
for "1" and "2"

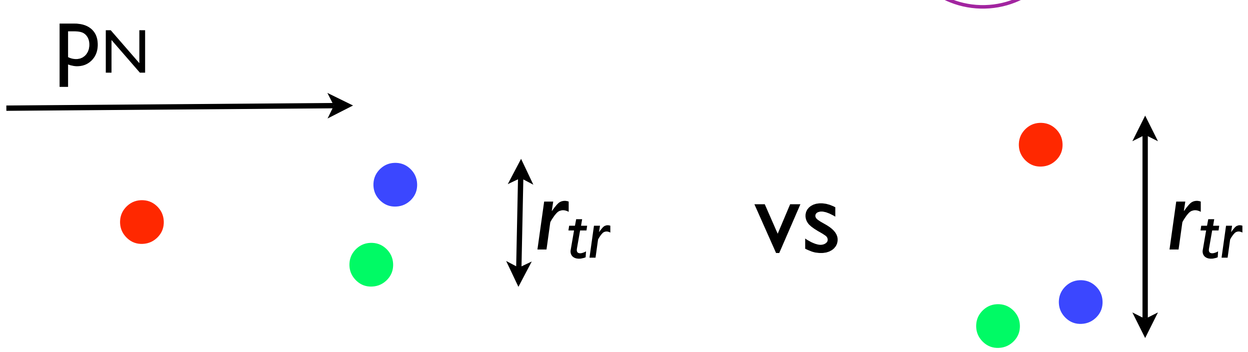
h+h'

$$|final\rangle = \lambda_1 a_1 |1\rangle +_2 a_2 |2\rangle)$$
$$= c_1 |h\rangle + c_2 |h'\rangle$$

elastic scattering
+inelastic diffraction

Are there global fluctuations of the strength of interaction of a fast nucleon, for example due to fluctuations of the size /orientation

$$|N\rangle = 3q + 3qg + 3q+\pi + \ldots$$

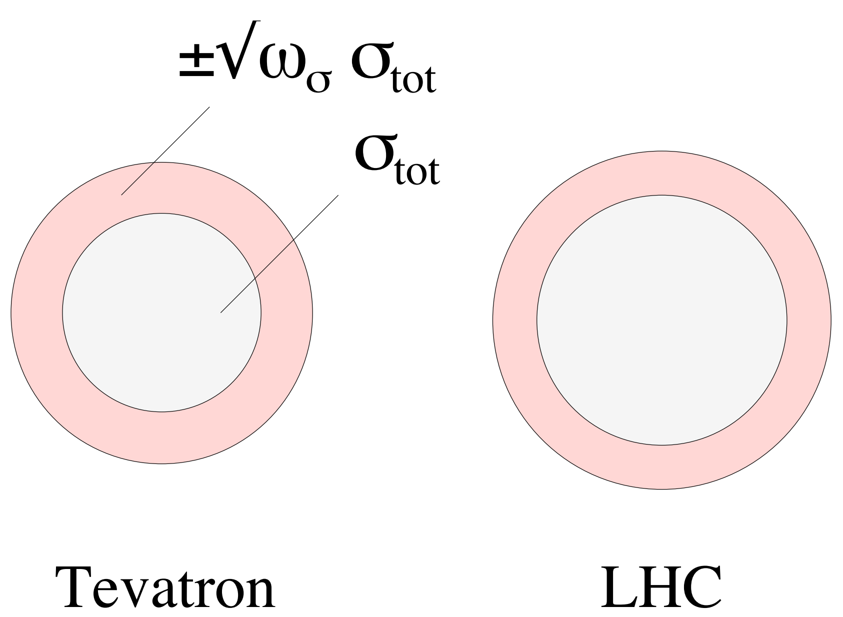


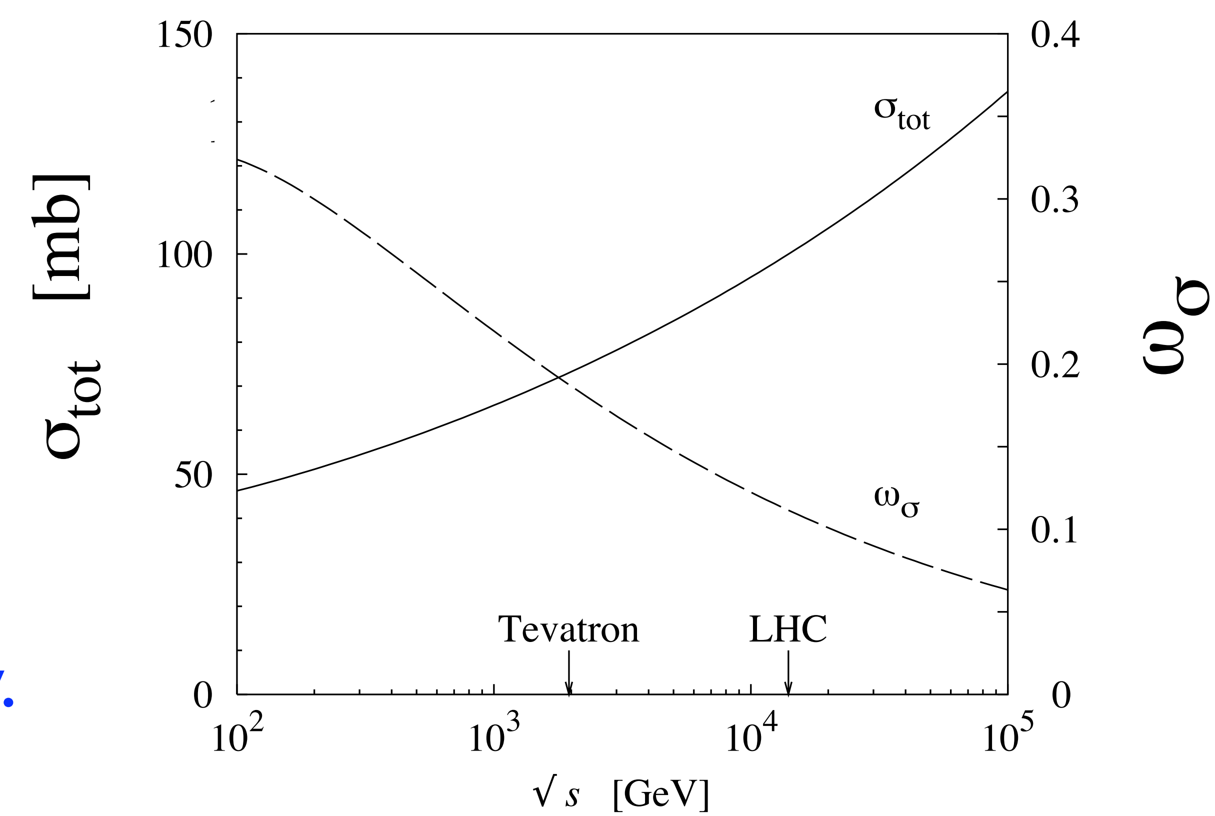
Due to a slow space-time evolution of the fast nucleon wave function one can treat the interaction as a superposition of interaction of configurations of different strength - Pomeranchuk & Feinberg, Good and Walker, Pumplin &Miettinen (in QCD this is reasonable for total cross sections and for diffraction at very small t)

Convenient quantity - $P(\sigma)$ -probability that nucleon interacts with cross section σ

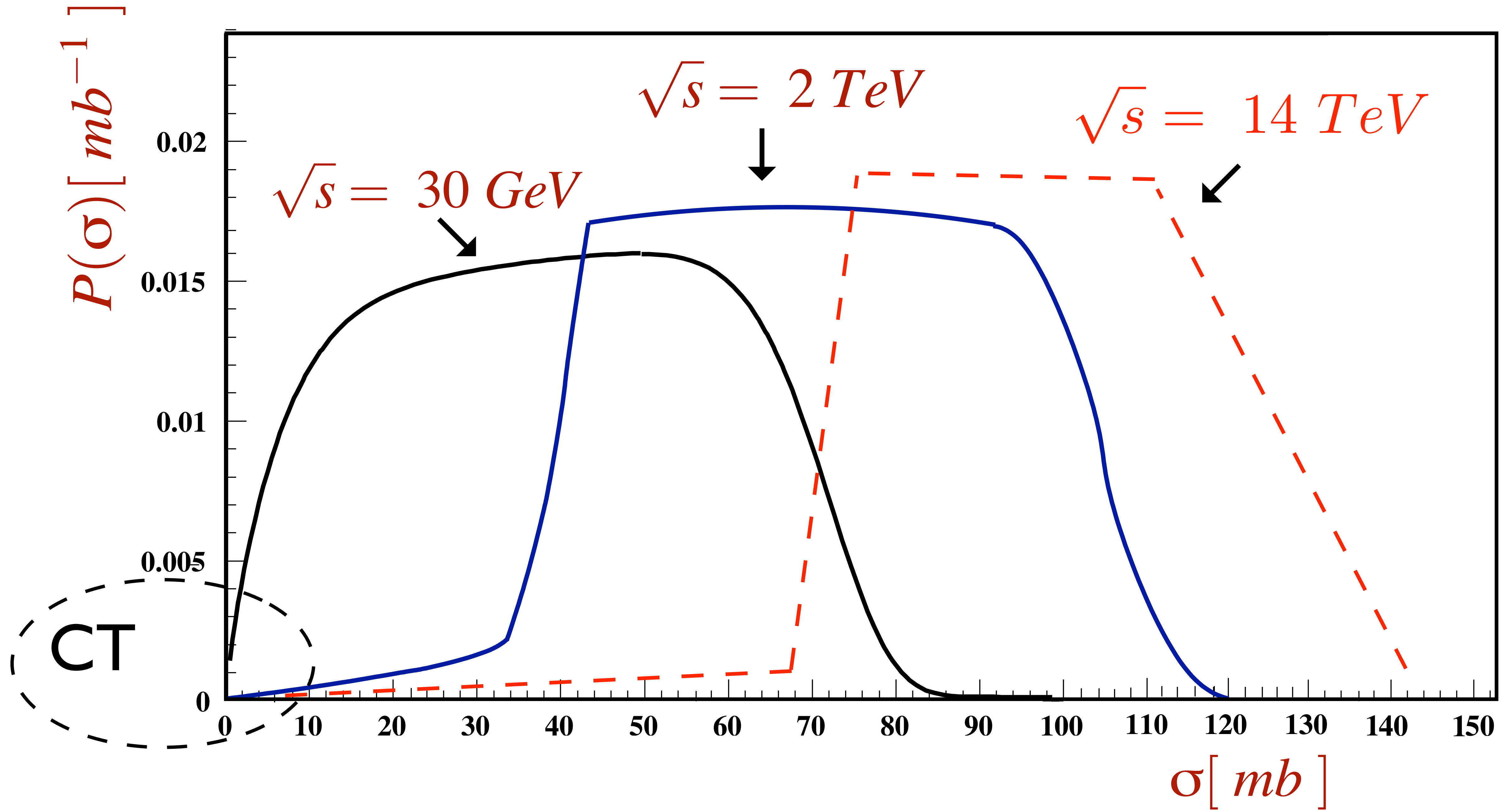
If there were no fluctuations of strength - there will be no inelastic diffraction at t=0:

$$\left.\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\right|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma)d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma \quad \text{variance}$$





Both small and large configurations grow. Periphery remains- still there is a correlation between σ and parton distributions -smaller σ, harder quark



The 30 GeV curve is result of the analysis (Baym et al 93) of the FNAL diffractive pp and pd data which explains FNAL diffractive pA data (Frankfurt, Miller, MS 93-97). The 14 and 2TeV curves are my guess based on matching with fixed target data and collider diffractive data.

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

Consider $\gamma_L^* + p \to V + X$ for Q^2 > few GeV^2

In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2| n)$ given by the expectation value of the twist--2 gluon operator in the state $|n\rangle$

$$G(x, Q^2) \;=\; \sum_n |a_n|^2 G(x, Q^2|n) \;\equiv\; \langle G\rangle$$

Making use of the completeness of partonic states, we find that the elastic(X = p) and total diffractive (X arbitrary) cross sections are proportional to

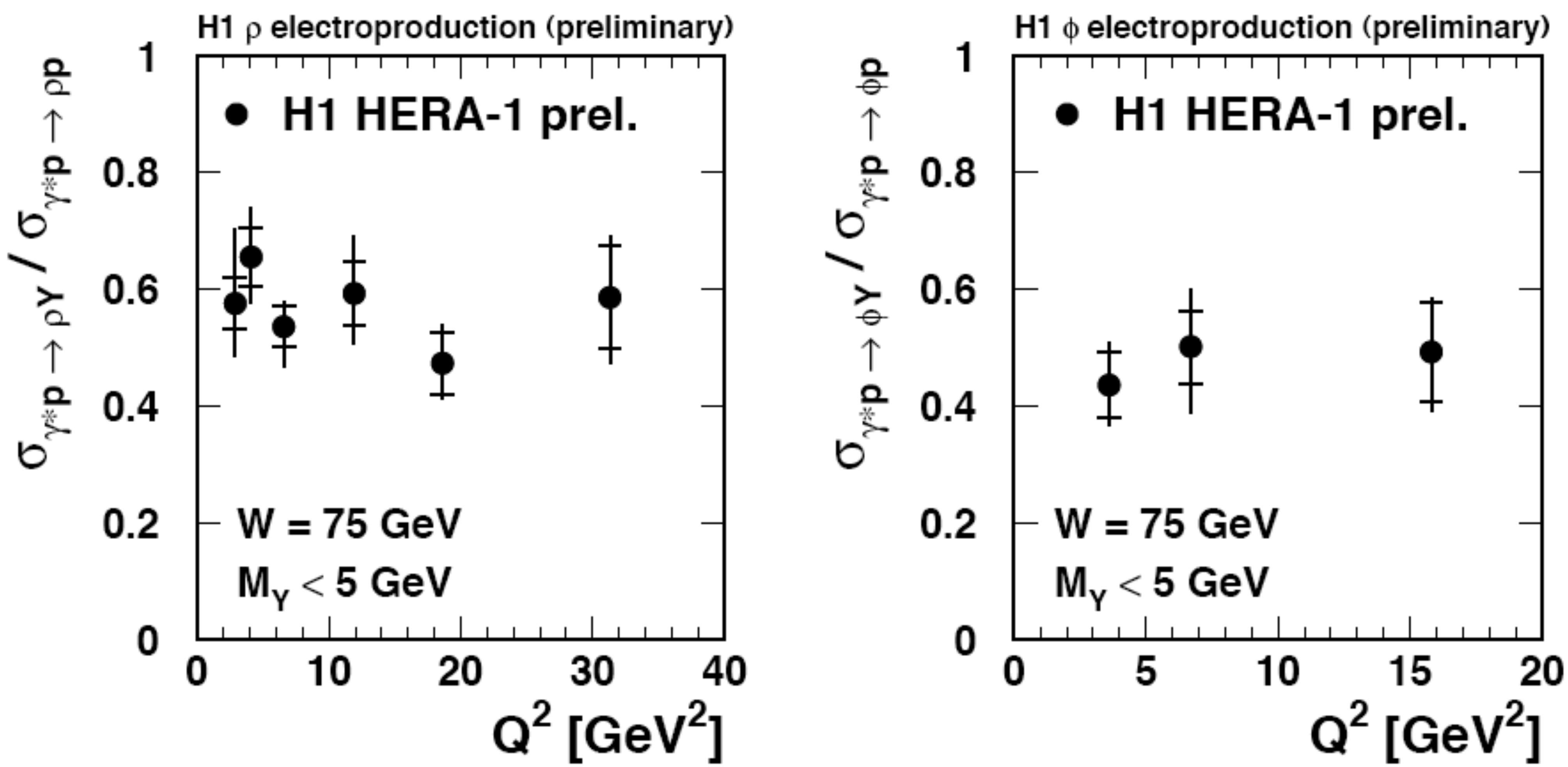
$$(d\sigma_{\rm el}/dt)_{t=0} \quad \propto \quad \left[\sum_n |a_n|^2 G(x,Q^2|n)\right]^2 \equiv \langle G\rangle^2,$$

$$(d\sigma_{\rm diff}/dt)_{t=0} \quad \propto \quad \sum_n |a_n|^2 \left[G(x,Q^2|n)\right]^2 \equiv \langle G^2\rangle.$$

Hence cross section of inelastic diffraction is $\quad \sigma_{\rm inel} = \sigma_{\rm diff} - \sigma_{\rm el}$

$$\Rightarrow \quad \boxed{\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \left.\frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Big/ \frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\right|_{t=0}}.$$

p-diss. / Elastic Ratio - *vs.* (Q^2)



- p-diss. / elastic ratio independent of Q^2
- Similar ratio within errors for ρ and ϕ

No official numbers for t -slopes - educ. guess

$B_{el} / B_{inel} \sim 3 \div 4$

$$\Rightarrow \quad \omega_g(Q^2 \sim \text{few GeV}^2, x \sim 10^{-3}) \sim 0.15 \div 0.2$$

Simple "scaling model" based on two assumptions

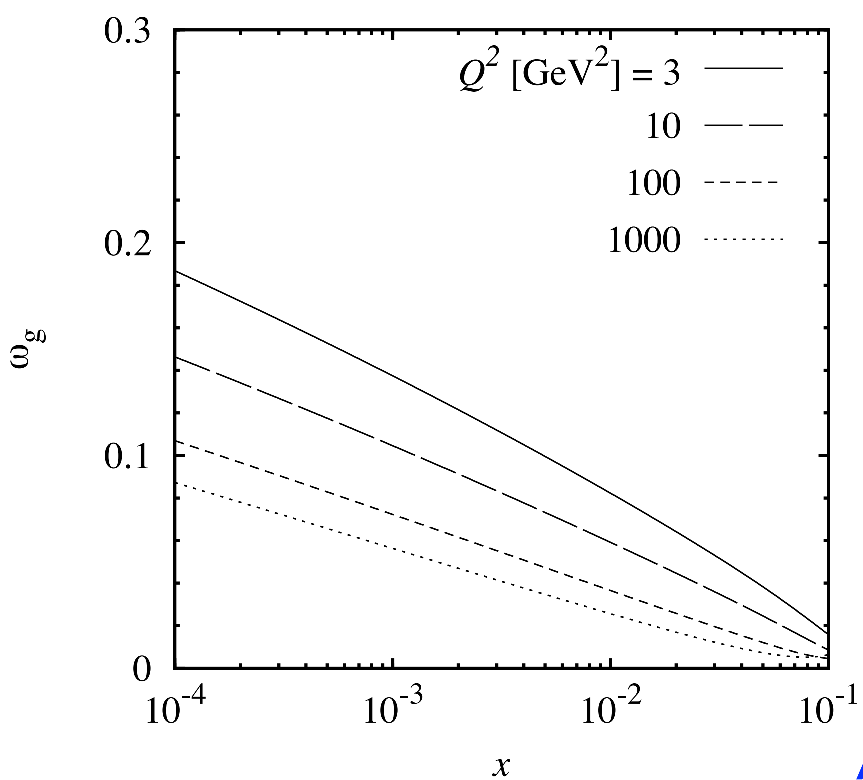
- At moderate energies $\sqrt{s}$ = 20 GeV the hadronic cross section of a configuration is proportional to the transverse area occupied by the color charges in that configuration,

$$\sigma \propto R^2_{\rm config}$$

- the normalization scale of the parton density changes proportionally to the size of the configuration $\mu^2 \propto R^{-2}_{\rm config} \propto \sigma^{-1}$ (in the spirit of Close et al 83 - EMC effect model)

$$G(x, Q^2\,|\sigma) \;=\; G(x, \xi Q^2) \qquad \xi(Q^2) \;\equiv\; (\sigma/\langle\sigma\rangle)^{\alpha_s(Q_0^2)/\alpha_s(Q^2)}$$

$$where\; Q_0^2 \sim 1\,\mathrm{GeV}^2$$



The dispersion of fluctuations of the gluon density, ω_g, as a function of x for several values of Q^2, as obtained from the scaling model

Warning: the model designed for small $x < 0.01$. There maybe other effects which could contribute to ω_g for large x

At the same time decrease of ω_g with Q^2 at x=const - generic effect

Gluon fluctuations have to be explored both theoretically and experimentally including implications for LHC final states

BFKL (Balitski, Fadin, Kuraev, Lipatov) regime at HERA - fundamental question what is the energy dependence of the cross section of interaction of two small dipole

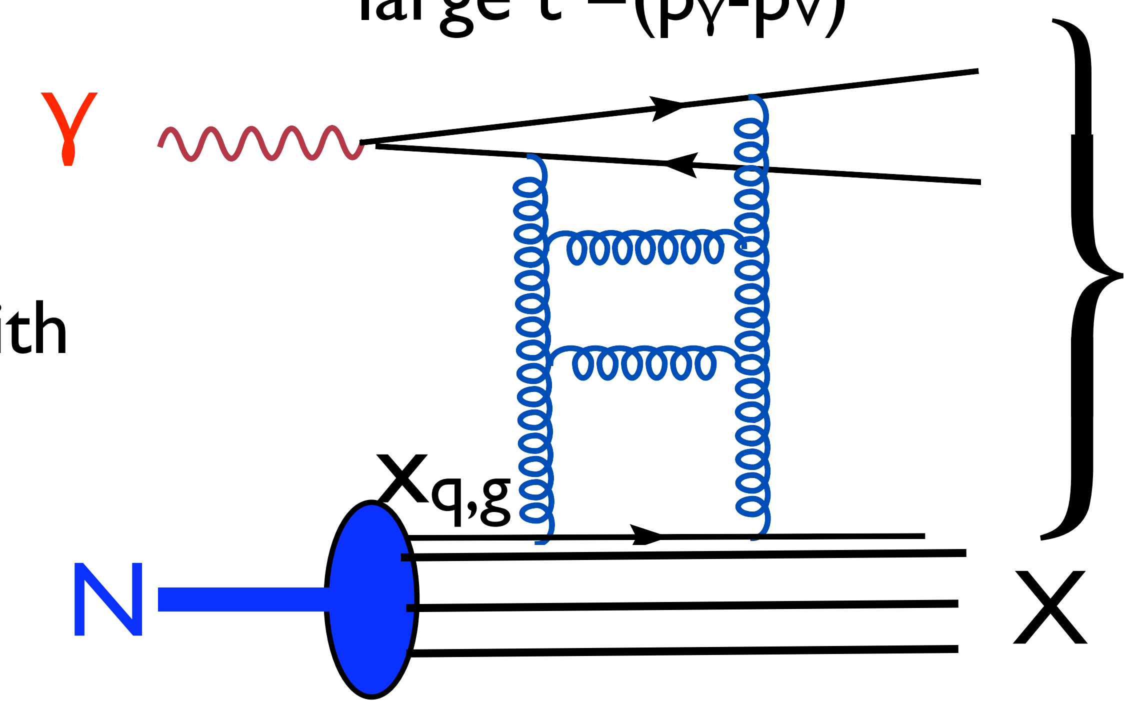
LO BFKL: $\sigma \sim s^{\delta}$, $\delta \sim 0.5 - 0.6$

NLO BFKL: $\delta \sim 0.2 - 0.25$

large $t = (p_{\gamma} - p_V)^2$

VM (ρ, J/ψ, γ)

HERA experiments reported agreement with LO BFKL



$$s' = x W^2_{\gamma p},$$

$$x = \frac{-t}{(-t + M_X^2 - m_N^2)}$$

The choice of large t ensures two important simplifications. First, *the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons*. Second is that *attachment of the ladder to two partons of the target is strongly suppressed*. Also the transverse size $\propto 1/\sqrt{-t}$

$$\frac{d\sigma_{\gamma+p\to V+X}}{dt\,dx} = \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16} g_p(x,t) + \sum_i (q_p^i(x,t) + \bar{q}_p^i(x,t))\right]$$

Recent analysis of Zhalov et al 08

For HERA cut of M_X^2/W^2 =const most of energy dependence from gluon density - BKFL with $\delta \sim 0.1 - 0.2$ is consistent with the data; soft Pomeron in this regime $\delta = -0.5$ is clearly out

EIC as good as HERA in terms of W' range with proper detector - can work at much larger $x \sim 0.2$

Conclusions

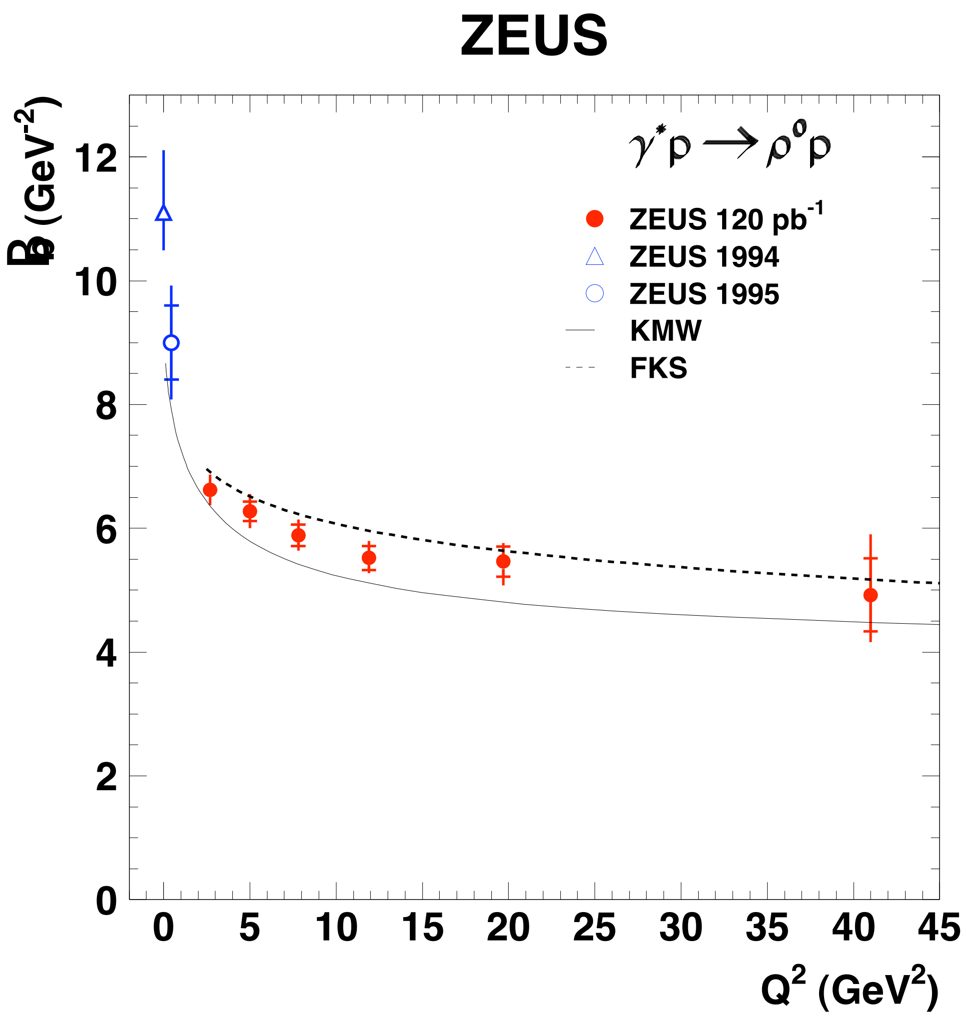
Impressive progress in the studies of hard diffractive processes at HERA. Success of QCD factorization theorems for diffraction

Connection to soft dynamics revealed

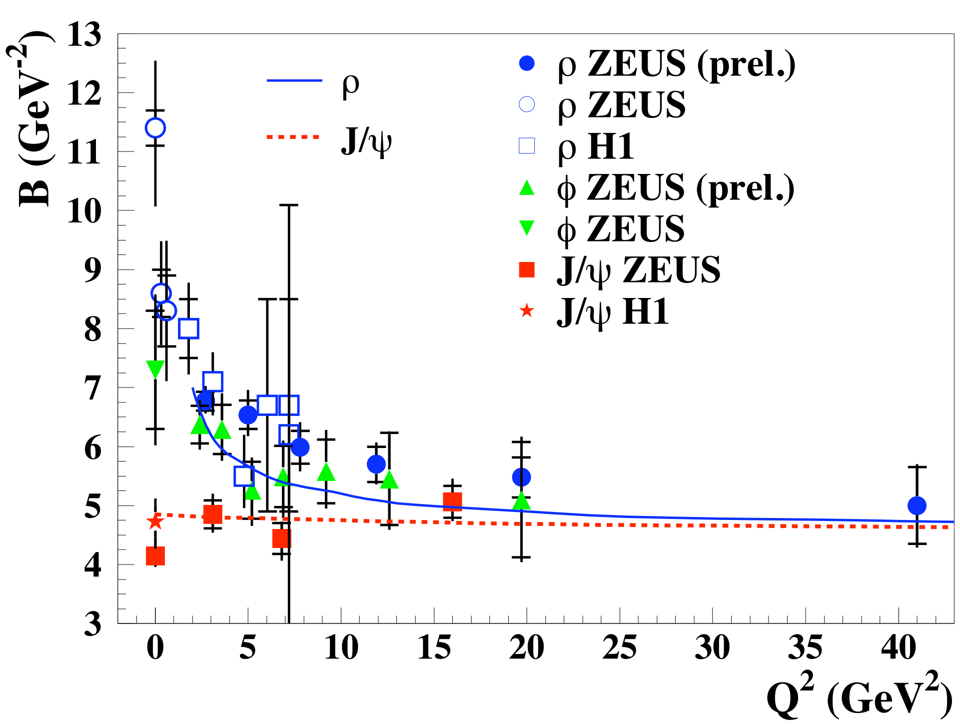
Evidence for fluctuations of small x gluon field in nucleon

Higher precision - new questions

Key to further progress good instrumentation of the nucleon fragmentation region. Missed opportunities at HERA



Drop of B is well reproduced by dipole models (in case of FKS actually a prediction of 10 years ago)



Convergence of the t-slopes, B of ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \rightarrow J/\psi + N$